Tests of Semiconductor Detectors for ATLAS Upgrade
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In Prague, 11 May 2017 

signature of the author
Název: Testování polovodičových detektorů pro ATLAS Upgrade

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Abstrakt: Předložená práce se koncentruje na testování prototypů ITk stripových modulů pomocí beta zářiče na ÚČJF v Praze v rámci projektu ATLAS Upgrade. Nová aparatura umožní srovnání výsledků s dalšími metodami testování modulů zahrnující laser nebo vysokoenergetický svazek částic. Aktivně jsem se podílel na sestavení celé aparatury, tvorbě kódů pro řadu automatizovaných měření použitím specializovaného softwaru ITSDAQ v prostředí ROOT a na následné analýze výsledků. Výstupem této práce je souhrn vlastností end-cap R0 DAQloadu s mini sensorem naměřených pomocí beta zářiče a charakterizačních testů čipu. Celkový sesbíraný náboj od beta elektronu odpovídá hodnotě 3.1 fC pro výchozí nastavení čipu a společně s často uváděným poměrem signál/šum vycházejícím 35 tvoří jedny z nejdůležitějších výsledků práce. Experimentální uspořádání pro testování beta zářičem spolu s celkovou analýzou výsledků bude nadále využitelné pro budoucí produkční fázi projektu.

Klíčová slova: testování beta zářičem, stripový křemíkový detektor, elektronika, ATLAS Upgrade

Title: Tests of Semiconductor Detectors for ATLAS Upgrade

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Abstract: This thesis is focused on beta source tests of prototypes of ITk Strip modules at IPNP in Prague in the framework of the ATLAS Upgrade project. New experimental apparatus will allow comparison of beta source test results with other testing methods including laser or test beam. I participated in the assembly of the whole apparatus, script development for a number of automated measurements using specialized ITSDAQ software and ROOT. Finally, summary of obtained properties of tested end-cap R0 DAQload with mini sensor is provided based on beta source tests and characterization of the readout chip. The resulting collected charge value corresponds to 3.1 fC and together with often referred quantity signal-to-noise ratio, which equals 35, it is one of the most important results of the thesis. The experimental arrangement including overall analysis of results will be usable for the future production phase of the project.

Keywords: beta source tests, strip silicon detector, electronics, ATLAS Upgrade
First I would like to thank to my supervisor of the master thesis RNDr. Peter Kodyš, CSc. for his patience, helpful approach and expert advice to the topic.

I would also like to thank to doc. RNDr. Zdeněk Doležal, Dr. and RNDr. Jiří Kroll, Ph.D. for their willingness to discuss unclear analysis results and other difficulties.

I am grateful to students from Prague strip group, namely Ondřej Theiner for laser setup tuning, Vít König for his contribution to FE parameters scans and Marek Martaus for automation of communication with individual laboratory devices.

Finally, my big thank you belongs to my family for peaceful and creative ambience.
# Contents

## Introduction

1 CERN

1.1 ATLAS

1.2 LHC and ATLAS Upgrade

1.2.1 ITk Upgrade

1.2.2 Strip Tracker

2 Silicon Modules

2.1 Basic Properties of Silicon

2.2 Silicon Doping

2.3 Migration of Charge Carriers

2.4 p-n Junction

2.5 Interaction of Particles in Silicon

2.6 Radiation Damage

3 Prague DAQload Installation

3.1 Readout system

3.2 Readout Hardware - The Atlys Board

3.3 Readout Software - ITSDAQ

3.3.1 Calibration and Performance Tests

3.3.2 Noise

3.4 External Trigger Setup

3.4.1 Beta Source

3.4.2 Scintillator

3.4.3 Signal Modification

3.5 Prague Laboratories

3.5.1 Additional Equipment

4 Source Tests and Analysis

4.1 Threshold Scan Analysis

4.1.1 Skewed Complementary Error Function Fit

4.1.2 Linear Fit

4.1.3 Cluster Size

4.2 Sensor Specification

4.3 Beta Source Test Results

4.3.1 Calibration Results

4.3.2 Source Tests at Room Temperature

4.3.3 Source Tests at Low Temperatures

4.4 FE Parameters Setting

4.4.1 Source Tests for Different FE Parameters Setting

4.4.2 Laser Tests for Different FE Parameters Setting

4.5 Estimation of Collected Charge Error

4.6 Measurement Discrepancies

4.6.1 Calibration Discrepancy
Natural development of technologies allows to advance the frontiers of high energy physics. Evolution in terms of increasing energy and luminosity is necessary also in case of such an accelerator as Large Hadron Collider in swiss CERN. Extensive upgrades of LHC magnets, pre-accelerators and detection systems are planned in the coming ten years. Higher intensity of proton collisions demands inter alia higher radiation hardness of subdetectors than some current detection systems can offer.

The ATLAS Upgrade project includes improvements of detection subsystems of the ATLAS experiment, one of the two major LHC detectors. It will require complete replacement of the Inner Detector by a new all-silicon Inner Tracker consisting of several layers of pixel and strip detectors. These ITk modules should be able to withstand fluences corresponding to integrated luminosity of upgraded High Luminosity LHC.

This diploma thesis concentrates on testing of prototypes of ITk Strip modules using beta source at the Institute of Particle and Nuclear Physics in Prague. The first chapter gives a brief overview of LHC pre-accelerators and experiments with a more detailed focus on the ATLAS detector and the ATLAS Upgrade project. In addition, there is described the arrangement of the new tracker together with strip module assembly. In the second chapter silicon properties are introduced including processes leading to charge collection as in the case of silicon sensor. This chapter contains also introduction to interaction of particles in silicon and radiation damage of silicon detectors. The description of beta source test setup can be found in the third chapter. It includes readout electronics, external trigger circuit, DAQload module placed in the black box and other laboratory equipment. A large part of this chapter is devoted to characterization scans of readout chip ABC130 provided by specialized ITSDAQ software. The fourth chapter presents all the beta source test and characterization results concerning the end-cap R0 DAQload module. In the fifth chapter the obtained source test results are discussed and compared to the test beam results.

Last three chapters present work performed mainly by author. The specific work of author consisted of the substantial contribution to setting up a source test system, performing most of the beta source measurements, substantial contribution to the data analysis software, data analysis of beta source tests and interpretation of final results.
1. CERN

CERN, the European Organization for Nuclear Research, uses the world’s largest system of synchrotrons for accelerating particles to the speed close to the speed of light. Its acronym is derived from French Conseil Européen pour la Recherche Nucléaire. CERN was founded in 1954 as a center of European particle physics and situated near Geneva on the Franco-Swiss border. Currently CERN comprises 22 member states including Romania, which joined in 2016.

In history, from the first synchrocyclotron to the world’s most powerful collider LHC, CERN’s accelerators helped us to understand properties of matter and made significant discoveries of new particles such as intermediate vector bosons $W^+$, $W^-$ and $Z^0$ in case of SPS in 1983 or Higgs scalar boson discovered by LHC in summer 2012. More about the history and development of not only CERN’s accelerators can be found in [9]. As a byproduct of the particle research the World Wide Web was also invented in 1989 at CERN by British scientist Tim Berners-Lee.

The complex of accelerators is able to reach maximum energy of protons in twenty minutes and consists of Linac 2 (Linear accelerator 2), Proton Synchrotron Booster, PS (Proton Synchrotron), SPS (Super Proton Synchrotron) and finally LHC (Large Hadron Collider). Operation of the LHC was started in 2008 and since 2012 it was able to achieve the centre of mass energy 8 TeV. After LS1 (Long Shutdown 1) between years 2013 and 2015 the LHC was successfully restarted and thanks to many upgrades the centre of mass energy raised to 13 TeV. Seven detector complexes are currently placed at the LHC[20]:

- ATLAS (A Toroidal LHC Apparatus)
- CMS (Compact Muon Solenoid) - complex detector, wide range of physics
- ALICE (A Large Ion Collider Experiment) - quark-gluon plasma study
- LHCb (Large Hadron Collider beauty) - b quark study, matter and antimatter differences
- LHCf (Large Hadron Collider forward) - cosmic ray simulations
- TOTEM (TOTal cross section, Elastic scattering and diffraction dissociation Measurement) - proton structure measurement
- MoEDAL (Monopole and Exotics Detector at the LHC) - magnetic monopole search

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[1] including Romania, which joined in 2016
1.1 ATLAS

ATLAS is, next to CMS, the general-purpose physics experiment at the LHC. It has operated since 2008. The detector itself weights 7,000 tons and is placed in cavern 100 meters below ground. Particle beams from the LHC collide at Point 1, where the ATLAS Detector is located, and produce new particles flying in all directions. Therefore the detector has cylindrical symmetry. The reconstruction of tracks, energies and other measured properties of various produced particles is complicated, so the detector is divided into several detection subsystems:

- Inner detector
- Calorimeter
- Muon spectrometer
- Magnet system

The inner detector is used to determine track, momentum and charge of incoming particles and consists of pixel detectors, SCT (SemiConductor Tracker) and TRT (Transition Radiation Tracker). Semiconductor pixel detectors are high-resolution detection components placed closest to the beam pipe and arranged in concentric cylinders. During LS1 three layers of pixels have been supplemented by the fourth one, the IBL (Insertable B-Layer), for Run 2. It increases the resolution in track and vertex reconstruction, which is crucial for b-tagging. The SCT consists of more than 4000 silicon microstrip two-sided modules arranged in 4 cylindrical barrel layers and 18 planar end-cap discs. The last layer of the inner detector is formed by the TRT that uses long narrow straw tubes filled with argon due to its frequent leaks from corroded pipes [16]. It can detect the transition of radiation photons created by passing a particle between straws.

The ATLAS calorimetry system measures energy deposited by particles produced in collisions and includes two complex components, the LAr (Liquid Argon) Calorimeter and the Tile Hadronic Calorimeter. The LAr is a sampling calorimeter with fine granularity divided into electromagnetic barrel and end-cap
calorimeter (EM), hadronic end-cap (HEC) and forward calorimeter (FCAL). It uses liquid argon as an active medium to collect ionization electrons and lead in the EM, copper in the HEC and first layer of the FCAL and tungsten in outer layers of the FCAL as a passive absorbing medium. The TileCal operates with half a million plastic scintillator tiles instead of argon. Passing particles cause the plastic to emit photons, which are consequently detected. The calorimeters are constructed to stop most of the passing particles except muons and neutrinos.

![Figure 1.2: Layout of the ATLAS detector](image)

Muons usually pass through the previous two detection systems undetected. Therefore, the third layer of ATLAS is the muon spectrometer, made up of 4,000 muon chambers divided into 4 specific subsystems. The CSC (Cathode Strip Chambers) are multi-wire proportional chambers with segmented cathode readout providing precision measurement of coordinates at ends of detector. The MDT (Monitored Drift Tubes) are formed by aluminium tubes filled by mixture of argon and carbon dioxide and measure curves of muon tracks. The RPC (Resistive Plate Chambers) placed in the barrel are made by bakelite plates interleaved by a gas mixture gap and provide muon triggering together with the second coordinate determination. The same task is performed by the TGC (Thin Gap Chambers) at ends of detector. Upgrades during LS1 allowed to install new or repaired RPC, CSC and TGC for increasing muon acceptance.

The ATLAS magnet system bends the tracks of particles to determine their charge and momentum. It is formed by the cylindrical Central Solenoid designed to provide a magnetic field 2 T. This superconducting solenoid shares the cryostat with the LAr calorimeter. The outer detector is influenced by a 4 T magnetic field from the Barrel and End-cap Toroid. The Barrel Toroid consists of 8 flat superconducting coils mounted symmetrically around the beam axis in the individual cryostats. The system is cooled by liquid helium at 4.7 K.
1.2 LHC and ATLAS Upgrade

The development of the ATLAS detector closely relates to the LHC upgrade, which will be performed in the following decade. At the present time, Run 2 is in progress with the peak luminosity $10^{34} \text{ cm}^{-2} \text{s}^{-1}$ and should deliver an integrated luminosity around 150 fb$^{-1}$. The next intermediate stage of LHC upgrades will include injector replacement (Linac 2 $\rightarrow$ Linac 4) during a two-year LS2 starting in 2019. Therefore, in Run 3 the peak and integrated luminosity should reach twice as high as during Run 2 at the center of mass energy 14 TeV.

![Figure 1.3: Long-term High Luminosity LHC upgrade plan](image)

Finally, during the 30-month LS3 since 2024 the HL-LHC (High Luminosity LHC) will be put into operation including upgraded SPS, new Superconducting Proton Linac (SPL) accelerating protons to the energy of 4 GeV and new PS2, which will be able to reach energy twice as high as present PS. The peak luminosity will be increased to $7.5 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$ and during its estimated time of operation ATLAS should collect integrated luminosity around 3000 fb$^{-1}$. This fact will allow rare channels of not only Higgs boson to be studied [18]. The LS3 ATLAS upgrade focuses inter alia on a new all silicon inner tracker.

1.2.1 ITk Upgrade

The current Inner Detector (ID) described above is not designed to meet the requirements of LS3 upgrade. One of the main reasons for its replacing is radiation damage of silicon detectors. The most resistant layer of the existing ID, the IBL, was designed for the fluences equivalent to 850 fb$^{-1}$, which is far below HL-LHC final requirements. The hit efficiency would reduce and the leakage current would exceed the limits of power supplies followed by the increase of the heat and insufficient cooling. There would be also problems in communication between chip front electronics (FE) and the read-out driver (ROD) or limitations resulting from the detector occupancy.

Therefore, a new all-silicon tracker will be installed during LS3. According to the current layout the ITk will consist of 5 central pixel layers, multiple end-cap pixel layers, 4 central strip layers and 6 end-cap strip layers. In Fig. 1.4 approved ITk layout with partly inclined pixel barrel modules is shown. The ITk will reach full coverage up to $|\eta| = 4$ and the cooling of sensors will be ensured by carbon dioxide at a temperature of minus 25 degrees.
1.2.2 Strip Tracker

Tracker Arrangement

The outer radii of the ITk will include strip modules operating with short strips (23.8 mm) in the two inner barrel layers and long strips (47.8 mm) in the two outer barrel layers. The strip modules in barrel will be organised in staves, each with 13 modules per side. End-cap disc will be populated with 32 identical petals and each of them will have nine modules per side arranged in six rings R0-R5. Design of petals and staves is shown in Fig. 1.5. Modules as a basic component of staves and petals are formed by gluing hybrids on the single-sided silicon detector. The front-end chips (ABC130) are then mounted on kapton printed circuit boards (PCBs) to make a hybrid (Fig. 1.6).

There have been fabricated two generations of short strip sensors, ATLAS07 and ATLAS12 with upgraded design, which have been also tested in Prague laboratory. Strips on the 320 µm sensor are AC-coupled with n-type implants in a p-type silicon bulk included p-stop isolation. In case of ATLAS12 series sensors additionally have a protection of AC-coupled capacitors against beam splash, reduction of the dead region of the sensors and modification to the bond pad layout. There are two types of ATLAS12 series, the ATLAS12A sensors with four rows of axial strips and the ATLAS12M sensors with two rows of axial strips.
and two rows of strips rotated of 40 mrad relative to the axial direction used in
an opposite side of the petals modules. It should help in measuring the second
coordinate of tracks. At the moment irradiated as well as unirradiated miniature
samples of sensors (1 cm$^2$) undergo tests.

![Assembly of short-strip barrel module](image)

Figure 1.6: Assembly of short-strip barrel module [22].

The strip sensors have to withstand fluence of $1.6 \times 10^{15} n_{eq}/cm^2$ and at the
end of HL-LHC operation the sensor specification signal-to-noise ratio is required
to range between 17-26 for different tracker regions [18].

**Strip Module Electronics**

Each sensor needs further electronics components to ensure data transfer. Up
to 256 strips can be wirebonded to the ABC130 read out chip referred to as
Application-Specific Integrated Circuit (ASIC) that uses 130 nm Complimentary
Metal Oxide Semiconductor (CMOS) construction technology. Two hybrids each
with up to 13 chips are mounted on a silicon sensor. Each hybrid has the HCC
(Hybrid Control Chip) that serves as an interface between chips and the EoS
(End of Substructure).

![Module electronics overview](image)

Figure 1.7: Module electronics overview [18].

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$^2$units correspond to 1 MeV neutron equivalent fluence per squared centimeter
Signals for readout of the HCC are provided by the EoS component called TTC (Trigger, Timing and Control) via TTC bus. The actual readout of HCCs is ensured by the GigaBit Transceiver (GBT) sending data to the fibre optic driver and then to the off-detector DAQ board.
2. Silicon Modules

The key to success of semiconductor detectors lies fundamentally in the appropriate selection of production material. Given that atoms of crystalline solid materials are arranged in a periodic lattice no discrete energy levels like in case of free atoms appear. Therefore, available energies of bound electrons form allowed bands. Differences in electrical conductivity of conductors, insulators and semiconductors can be explained in terms of their energy bands and gaps.

Conductors are characterized by overlapping valence and conduction bands (Zn or Pb) and no band gap. On the other hand insulators (e.g. SiO\textsubscript{2}) have a large band gap around 9 eV, which doesn’t allow good conductivity at the room temperature. In a semiconductor less energy is needed for electron in the valence band to excite. In case of silicon the gap equals 1.12 eV at temperature 300 K and the average energy for electron-hole pair creation corresponds to 3.6 eV.

Besides silicon also germanium is widespread in high energy physics, which became useful in gamma ray detection thanks to the higher atomic number.

<table>
<thead>
<tr>
<th>Property</th>
<th>Si</th>
<th>Ge</th>
<th>GaAs</th>
<th>Diamond</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic Number</td>
<td>14</td>
<td>32</td>
<td>31/33</td>
<td>6</td>
</tr>
<tr>
<td>Atomic Mass [amu]</td>
<td>28.1</td>
<td>72.6</td>
<td>144.6</td>
<td>12.6</td>
</tr>
<tr>
<td>Band Gap [eV]</td>
<td>1.12</td>
<td>0.66</td>
<td>1.42</td>
<td>5.5</td>
</tr>
<tr>
<td>Radiation Length $X_0$ [cm]</td>
<td>9.4</td>
<td>2.3</td>
<td>2.3</td>
<td>18.8</td>
</tr>
<tr>
<td>Average Energy for Creation of an Electron-Hole Pair [eV]</td>
<td>3.6</td>
<td>2.9</td>
<td>4.1</td>
<td>$\sim 13$</td>
</tr>
<tr>
<td>Average Energy Loss $dE/dx$ [MeV/cm]</td>
<td>3.9</td>
<td>7.5</td>
<td>7.7</td>
<td>3.8</td>
</tr>
<tr>
<td>Average Signal [e$^-$/\mu m]</td>
<td>110</td>
<td>260</td>
<td>173</td>
<td>$\sim 50$</td>
</tr>
<tr>
<td>Intrinsic Charge Carrier</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concentration [cm$^{-3}$]</td>
<td>$1.5\cdot 10^{10}$</td>
<td>$2.4\cdot 10^{13}$</td>
<td>$1.8\cdot 10^6$</td>
<td>$&lt; 10^3$</td>
</tr>
<tr>
<td>Electron Mobility [cm$^2$/Vs]</td>
<td>1500</td>
<td>3900</td>
<td>8500</td>
<td>1800</td>
</tr>
<tr>
<td>Hole Mobility [cm$^2$/Vs]</td>
<td>450</td>
<td>1900</td>
<td>400</td>
<td>1200</td>
</tr>
</tbody>
</table>

Figure 2.1: Scheme of gaps between valence and conduction band for (a) conductors with partially filled conduction band or with the overlapping bands, (b) semiconductors and (c) insulators [8].

Figure 2.2: Comparison of semiconductors properties [15].
Other possibilities of frequently used semiconductors represent compound GaAs serving for a construction of integrated circuits or rare and expensive diamonds with boron impurity. In Fig. 2.2 comparison of some basic properties of these semiconductors can be found.

2.1 Basic Properties of Silicon

Silicon, a member of IV group, as the 14th element of the periodic table is the second abundant element in the Earth’s crust and the eighth most common element in the universe. It occurs in nature mostly in the form of silicon dioxide (silica) as quartz. Pure silicon must be produced in an electric arc furnace by reducing silicon dioxide using SiO$_2$ + 2C $\rightarrow$ Si + 2CO[1]. Silicon mono-crystal used in a production of silicon wafers is grown mostly by the Czochralski process from doped (as required) poly-crystalline silicon. There are several advantages compared to other types of tracking detectors (e.g. gas chambers):

- Small average energy for e-h pair creation (3.6 eV), nearly 10 times less than in case of gas trackers
- High ionization losses due to high density (2.37 g/cm$^3$), so that the thickness of the silicon detector can be significantly reduced (300 µm) relative to large gas chambers
- Short range of secondary $\delta$-electrons indicates better spatial resolution
- Mechanical strength of the material
- Good compatibility with other electronic devices and circuits made of silicon wafers
- Possibility to control charge carriers concentration by silicon doping
- High mobility of charge carriers increases rate of reading and decreases dead time, quick response (10 ns)

But signal from the silicon detector is proportional only to its thickness unlike gas trackers, which offer multiplication of the signal generated by primary particles. However, even higher cost doesn’t outweigh advantages of silicon trackers described above.

2.2 Silicon Doping

Intrinsic semiconductor contains only atoms of the same type without adding dopants. The conductivity of this semiconductor type is realized by thermally excited electrons in a conduction band. The excitation process creates also positively charged holes in a valence band that contribute together with electrons in an electric field to the overall conductivity. The number of generated charge

\[1\] for the highest possible silicon purity more complicated process is used including SiC, HCl and hydrogen

12
carriers strongly depends on ambient temperature. The concentration of intrinsic charge carriers (e.g. electrons) according to statistical physics can be written as
\[ n = \int_{E_g}^{+\infty} D_e(E)f_e(E)dE \tag{2.1} \]
where \( E_g \) represents the band gap energy, \( D_e(E) \) density of states (derived e.g. in [1])
\[ D_e(E) = \frac{1}{2\pi^2} \left( \frac{2m_e}{\hbar^2} \right)^{3/2} (E - E_g)^{1/2} \tag{2.2} \]
and \( f_e(E) \) the Fermi-Dirac function for system of fermions:
\[ f_e(E) = \frac{1}{1 + e^{\frac{E - E_F}{kT}}} \tag{2.3} \]
From the mentioned equations the resulting concentration of free electrons can be calculated considering that \( E_F \) obviously (relation 2.3) indicates energy with 50 percent probability of occupation called the Fermi level:
\[ n = 2 \left( \frac{m_e kT}{2\pi \hbar^2} \right)^{3/2} e^{\frac{E_F - E_g}{kT}} \tag{2.4} \]
In analogy with the previous calculation the concentration of holes is
\[ p = 2 \left( \frac{m_h kT}{2\pi \hbar^2} \right)^{3/2} e^{-\frac{E_F}{kT}} \tag{2.5} \]
Given that in case of intrinsic silicon without any impurities or dopants it exists for each electron just one hole, the charge carriers concentrations are independent of the value of Fermi energy:
\[ n_i = h_i = \sqrt{np} = 2 \left( \frac{kT}{2\pi \hbar^2} \right)^{3/2} (m_e m_h)^{3/4} e^{\frac{-E_g}{kT}} \tag{2.6} \]
Silicon has a diamond lattice structure that belongs to the fcc crystal family. Each atom is surrounded by four neighbors and shares with them its four valence electrons forming covalent bonding. It is impossible to get intrinsic pure silicon in practice, so that some impurities in lattice usually appear. But often they are intentionally doped into silicon lattice to improve an electrical conductivity (Fig. 2.3) by creating extra energy level in a forbidden band. Such a semiconductor enriched by dopants is called extrinsic. Impurities can be divided into two groups:

- Donor impurity (P, As, Sb)
- Acceptor impurity (B, Al, Ga, In)

The pentavalent donor impurity with five valence electrons in a silicon tetra-valent lattice causes small binding energy of the fifth electron, which is more likely ionized to a conduction band. Higher number of electrons increases chance to recombination and the silicon becomes so called n-type because of the predominant negative charge carriers.
Figure 2.3: Schematic tetravalent lattice for a) n-type silicon with donor (As) and 
b) p-type silicon with acceptor (B) [8].

The tetravalent acceptor impurity with three valence electrons in a silicon 
tetravalent lattice causes jump of an electron to the empty place in a valence 
band to form covalent bond and the resulting creating of a hole. This fact leads 
to the higher number of the positive charge carriers and the silicon becomes so 
called p-type.

Figure 2.4: Donor and acceptor energy levels in a forbidden band of silicon. Energy 
values above the dashed line are calculated from the upper edge and below the 
dashed line from the lower edge [8].

We can estimate the ionization energy for the donor $E_D$ using Bohr atom 
model with different permittivity $\epsilon_s$ and effective electron mass $m_e$:

$$E_D = \left( \frac{\epsilon_0}{\epsilon_s} \right)^2 \left( \frac{m_n}{m_0} \right) E_H \quad (2.7)$$

---

2The effective electron mass depends on properties of semiconductor and is defined as the 
inverted second derivation of electron energy with respect to momentum. For silicon it equals 
$0.19m_0$. [8]
where

\[ E_H = \frac{-m_0 q^4}{8 (\epsilon_0 n h)^2} = -\frac{13.6eV}{n^2} \quad (2.8) \]

The quantity \( m_0 \) represents the free-electron mass, \( q \) electron charge, \( \epsilon_0 \) permittivity of vacuum, \( h \) Planck constant and \( n \) the principal quantum number.

Explicit values of ionization energy for various dopants are shown in Fig. 2.4. Regarding density of charge carriers, we can obtain for silicon with dopants (\( N_A \) acceptors and \( N_D \) donors) [7]:

\[ n = n_i e^{\frac{E_{Fe} - E_F}{kT}} = \frac{1}{2} \left[ N_D - N_A + \sqrt{(N_D - N_A)^2 + 4n_i^2} \right] \approx N_D \quad (2.9) \]

\[ p = n_i e^{\frac{E_F - E_{Fe}}{kT}} = \frac{1}{2} \left[ N_A - N_D + \sqrt{(N_D - N_A)^2 + 4n_i^2} \right] \approx N_A \quad (2.10) \]

where \( E_{Fe} \) is the Fermi level of extrinsic silicon.

### 2.3 Migration of Charge Carriers

As mentioned above charge carriers in doped silicon are essentially free particles with three degrees of freedom as they can move about in a three-dimensional space. Therefore, their mean kinetic energy equals \( \frac{3}{2} kT \) and mean shift of particles tends to zero.

To collect free charge carriers an outer electric field \( \vec{E} \) is used and the resulting force applied to the particles causes their oriented movement. This process is called drift and the attained velocity equals

\[ \vec{v}_{n,p} = \mp \frac{q \tau_c}{m_{n,p}} \vec{E} \equiv \mp \mu_{n,p} \vec{E} \quad (2.11) \]

where \( \tau_c \), the mean free time, represents the average time between collisions with scattering centers such as lattice and impurity atoms and \( \mu_{n,p} \) is defined as a drift mobility of electrons, resp. holes.

Another important current component can appear if there is a spatial variation of charge carrier concentration in silicon. This diffusion process leads to particle flow from a region of high carrier concentration to a region of low concentration:

\[ \vec{F} = -v_{th} l \vec{\nabla} n \equiv -D \vec{\nabla} n \quad (2.12) \]

Random thermal motion of carriers is characterized by a thermal velocity \( v_{th} \) and a mean free path \( l = v_{th} \tau_c \). The diffusivity \( D \) is related to the drift mobility by the Einstein relation

\[ D = \frac{kT}{q} \mu \quad (2.13) \]

coming from the zero net flow condition at equilibrium.
2.4 p-n Junction

A p-n junction is widely used component in electronic applications, especially in silicon detector construction. It is formed on the transition of two oppositely doted neutral silicon wafers, where the different Fermi levels lead to diffusion and recombination of free charge carriers. Consequently, n-type silicon region near the junction becomes positively charged in contrast with negatively charged p-type silicon region. This space with net charge is called depletion region where an electric field arises with a potential barrier $V_{bi}$ (Fig. 2.5b). Assuming $n = N_D$ in equation [2.9] and $p = N_A$ in [2.10] with different Fermi levels in n- and p-type crystals $E_A$ and $E_D$, we get

$$V_{bi} = \frac{E_A - E_D}{q} = \frac{kT}{q} \ln \left( \frac{N_A N_D}{n_i^2} \right)$$  \hspace{1cm} (2.14)

By taking into account an applied external electric field, there are two possible ways of connection:

- **Forward bias** - positive electrode connected to p-type silicon
- **Reverse bias** - positive electrode connected to n-type silicon

In the connection of forward bias holes and electrons are pushed towards the junction and the depletion zone becomes narrower. Therefore, the reverse biased p-n junction became crucial not only for semiconductor detection systems in high energy physics because it makes the depletion region wider and the diffusion across the junction is suppressed.

![Figure 2.5: a) Charge carriers concentration in the region of p-n junction and b) the distribution of an electric field with marked built-in potential [8].](image)

Given that in the depletion region no free charge carriers appear, the Poisson’s equation can be written as [9].

---

16
\[
\frac{d^2 \phi}{dx^2} = -\frac{\rho}{\epsilon}
\]  

(2.15)

where we assume the permittivity of silicon \( \epsilon \) and the charge distribution \( \rho \) in the depletion zone from \(-x_p\) to \(x_n\) (Fig. 2.5a):

\[
\rho = \begin{cases} 
-eN_A, & -x_p < x \leq 0 \\
eN_D, & 0 < x < x_n 
\end{cases}
\]

(2.16)

and the total depletion region width obviously corresponds to

\[
W = x_p + x_n
\]

(2.17)

Considering the crystal neutrality, the equation 2.15 can be solved. Let’s suppose that the impurity concentration on one side of the junction prevails (e.g. \( N_A \gg N_D \)) then the depletion zone width depending on the built-in potential and doping equals

\[
W = \sqrt{\frac{2\epsilon}{e} \left( \frac{N_A + N_D}{N_A N_D} \right) V_{bi}} \approx \sqrt{\frac{2eV_{bi}}{eN_D}}
\]

(2.18)

Since the large accumulated charge is on the both sides of the junction, the depletion layer acts like a capacitor. The increment of charge \( dQ \) causes an increase of the barrier voltage \( dV_{bi} = WdQ/\epsilon \). The junction depletion region capacitance is then given by

\[
C_j = \frac{dQ}{dV_{bi}} = \frac{\epsilon}{W} \approx \sqrt{\frac{\epsilon eN_D}{2V_{bi}}}
\]

(2.19)

### 2.5 Interaction of Particles in Silicon

Charged particles in solids, especially leptons, lose their energy by interactions with electrons of atoms (ionization) or by a radiation of photons in the Coulomb field of atomic nuclei (bremsstrahlung). Additional processes that cause energy losses in material are Coulomb scattering (especially in thicker layers) or high energy secondary \( \delta \)-electrons. We can divide energy losses on the radiation and ionization part:

\[
\frac{dE}{dx} = \left( \frac{dE}{dx} \right)_{\text{ion}} + \left( \frac{dE}{dx} \right)_{\text{rad}}
\]

(2.20)

The ionization part of mean energy loss for the passing particle of charge \( z \) is described by an integral from the minimal energy loss \( T_{min} \) (ionization potential) to the maximal energy loss \( T_{max} \) of the product of the Rutherford scattering cross-section and the density of electrons \( n_e \) in material. This relation is called Bethe-Bloch formula [7]

\[
- \left( \frac{dE}{dx} \right)_{\text{ion}} = \int_{T_{min}}^{T_{max}} T n_e \frac{d\sigma_{Rath}}{dT} dT = \frac{4\pi\alpha^2\hbar^2z^2Z}{m_e\beta^2A} \rho N_A \ln \left( \frac{T_{max}}{T_{min}} \right)
\]

(2.21)
where \( m_e \) represents electron mass, \( N_A \) Avogadro constant and the material is characterized by atomic number \( Z \), atomic weight \( A \) and density \( \rho \). Maximal transferable kinetic energy is given by

\[
T_{\text{max}} = \frac{2m_e\beta^2\gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2}
\] (2.22)

The relation 2.21 can be rewritten for fast electrons to [5]

\[
-\left(\frac{dE}{dx}\right)_{\text{ion},e^-} = \frac{2\pi\alpha^2\hbar^2z^2Z}{m_e\beta^2A}\rho N_A \left[ \ln \left( \frac{m_e\beta^2E}{2I(1-\beta^2)} \right) - \ln 2 \sqrt{1-\beta^2 + \beta^2 - 1} + 1 - \beta^2 + \frac{1}{8} \left( 1 - \sqrt{1-\beta^2} \right)^2 \right]
\] (2.23)

including velocity \( \beta = v/c \) and the average excitation and ionization potential \( I \) of the material. Set the factor before the bracket \( \xi \).

In detectors of moderate thickness \( x \) the energy loss probability distribution is described by the highly-skewed Landau-Vavilov-Bischel function whose most probable value is [10]

\[
\Delta_p = \xi x \left[ \ln \frac{2m_e\beta^2\gamma^2}{I} + \ln \frac{\xi x}{I} + j - \beta^2 - \delta(\beta\gamma) \right]
\] (2.24)

where factor \( j \) equals 0.2 and \( \delta(\beta\gamma) \) represents density correction.

![Figure 2.6: Normalized Landau-Vavilov-Bischel energy loss probability distribution in silicon for 500 MeV pions [10].](image)
The radiation part of energy loss due to bremsstrahlung is described by formula [7]

\[- \left( \frac{dE}{dx} \right)_{\text{brems,e}} = \frac{\alpha^2 \hbar^2 \gamma Z (Z + 1) N_A \rho}{137 m_e A} \left[ 4 \ln 2 \gamma - \frac{4}{3} \right] \]  

(2.25)

### 2.6 Radiation Damage

Semiconductors are generally sensitive to radiation. During collisions silicon sensors must withstand a huge amount of high energy particles that cause increasing radiation damage in detectors. The defects in the silicon lattice lead to the formation of discrete trapping levels in the forbidden band and the subsequent reduction of charge carriers. Consequently several undesired effects occur [1]:

- Increase of leakage current (current flowing through the depletion zone due to thermal generation of e-h pairs in detector bulk or geometry, humidity and purity of surface materials)
- Decrease of energy resolution due to reduction of charge carriers at the electronics input
- Charge mobility reduction
- Increase of charge collection time
- Semiconductor type inversion (appears at currents higher than $10^{13} \text{n}_{eq}\text{cm}^{-2}$, donors are removed and acceptors are created in their place)

![Figure 2.7: Depletion voltage and concentration of charge carriers for different fluence values of irradiation [11].](image)

The bulk leakage current is essentially linear function of radiation fluence $\Phi$ with the damage constant $\alpha$, which depends on the energy and type of radiation. The increase of the leakage current can be then calculated as

\[ \Delta I = \alpha V \Phi \]  

(2.26)
where $V$ represents the volume of depletion detector. As shown in Fig. 2.7, also the depletion voltage increases after type inversion.

Heavy charged particles such as protons and neutrons can transmit a large recoil energy to the bulk and create so called clusters of damage (areas with many traps) apart from electrons that cause primarily single defects. These defects can be partly fixed after stopping of irradiation by temporary rise in temperature. This process is called annealing and in silicon remains useful about 80 minutes at a temperature of 60 degrees [11].
3. Prague DAQload Installation

The replacement of the ATLAS Inner Detector (ID) by the ATLAS Inner Tracker (ITk) will be realised during HL-LHC upgrade in 2024, but preparation for this process requires very detailed testing of new modules by now. Production of the ITk modules, sensors and hybrids should be started in 2017. However, a lot of module prototypes have been measured in collaborating institutes including Institute of Particle and Nuclear Physics in Prague and at test beams.

3.1 Readout system

As mentioned in Sec. 1 the pre-production of the ATLAS Strip ITk has started with 250 nm ASICs called ABCn25 that brought mainly the powering evolution from the independent hybrids powering used for SCT to the powering with DC-DC conversion. For detailed testing fully assembled ASICs with 130 nm construction technology named ABC130 were ready recently. In Fig. 3.1 three different ABC130 prototypes of strip ITk modules are shown including end-cap module called DAQload with ATLAS12 mini-sensor that has been tested also in Prague laboratory.

![Figure 3.1: ABC130 Short-Strip Barrel Module (left), Long-Strip Barrel Module (centre) and end-cap DAQload (right)](image)

The currently tested modules use a daisy chain routing from the ABC130 readout chips to the HCC130, but a new star configuration of routing, which is designed for ITk strip modules produced in future, connects directly ABCStar and HCCStar chips without a bottleneck in data transfer. The ABCStar chip as well as the ABC130 chip will process signal from 256 strips of the silicon detector and will ensure a binary readout.

The ABC130 chip differs from the previous versions by reading out two rows of strips, lower necessary external voltage or three different trigger types (L0, L1, R3 - Fig. 3.2). After pulse modification by preamplifier-shapers and discriminators the binary data are stored in the pipeline (L0) for 6.4 $\mu$s (256 slots $\times$ latency time 25 ns) or read by an external trigger during this time. As described in Sec. 1 readout from HCC chips is performed by an external electronics signal via EoS of module.
3.2 Readout Hardware - The Atlys Board

Readout electronics, especially for beta source tests, plays a major role in an experimental setup, because it ensures communication between module, external trigger and PC. During tests in Prague the Atlys circuit board replaced older High Speed Input Output (HSIO) board, which was used until the end of 2016 for laser tests, to allow smaller setups and reduce the cost. The Atlys board has sufficient resources to manage 8 modules and is able to support other digital boards needed to built source test setup:

- **VMOD-IB** - communication with module
- **PMOD-TTC** - input/output of trigger
The VMOD-IB board is connected via 16 way IDC ribbon cable to the low-voltage differential signaling (LVDS) board that is mounted to the test frame via Samtec connectors. It provides data flow from the EoS to the computer based software and is sufficient for sensor and chip characterization. However, as we would like to perform beta source tests, we need to use an external signal from trigger setup for readout. Therefore, Trigger IO board have to be included and connected to the Atlys.

This arrangement is related to the necessity of trigger delay setting in the software (called latency) to get the correct data packet from ABC130 pipeline. In addition, the connection of the PMOD-TTC board to the Atlys requires appropriate firmware installation after each switching on of the Atlys.

This arrangement is related to the necessity of trigger delay setting in the software (called latency) to get the correct data packet from ABC130 pipeline. In addition, the connection of the PMOD-TTC board to the Atlys requires appropriate firmware installation after each switching on of the Atlys.

![Digilent Adept software and Atlys configuration.](image)

The Atlys micro-USB connector allows firmware programming using the Digilent Adept software by choosing the corresponding firmware version (e.g. atlys_itsdaq_va102_TTC.bit) and clicking on Program button.

### 3.3 Readout Software - ITSDAQ

The ITk project uses ATLAS ITk Strips DAQ (ITSDAQ) as a readout software for Windows and Linux systems, which is an updated version of the previous software SCTDAQ for Semiconductor Tracker. It supports the readout hardware such as Atlys, Nexys Video board or HSIO.

For the purpose of the preparation for beta and laser tests of Prague DAQload the newest (December 2016) trunk version 4635 of ITSDAQ was installed on
computers ipnp03, ipnp14 and ipnp28. However, there were several requirements for the smooth run of the software that have to be done before its launch:

- Install Microsoft Visual C++ (MSVC) 2015
- Install a scientific software framework ROOT (version 5.34/36)
- Perform a couple of file corrections according to [13]

ITSDAQ allows setting of various chip parameters and scan variables that characterize the measurement. Each measurement is marked by three numbers, namely run, scan and burst number. After running the program the Burst Data and the Scan Data software windows appear in addition to the ROOT command window. The Burst Data window provides a possibility of manual setting of scan parameters and shows the actual data packets from the bonded channels of the sensor. The Scan Data window shows the final result of each scan.

![Burst Data window of the ITSDAQ software.](image)

Furthermore the software requires the creation of the specific folder tree called `../sctvar/` to save important results from scans including the following subdirectories:

- `data/` - storage of root files with detailed ntuples
- `results/` - storage predominantly of text files with the most important results
- `macros/` - space for user macros
- `ps/` - storage of run plots in pdf files
- `config/` - files for the initial configuration of module parameters loaded during ITSDAQ start
3.3.1 Calibration and Performance Tests

Before the actual beta or laser sensor test we need to check basic properties of the module by its response during performance tests and calibration. The calibration is usually done after each change in configuration files to reach adequate timing and response variability for each channel. The basic calibration scans are part of installed ITSDAQ macros and directly executable from the Burst Data panel.

Threshold Scan

Calibration tests work on the principle of charge injection through the calibration circuit to the channels and a gradual increase of the discriminator threshold value. This type of test is called threshold scan and becomes the basis of the ABC130 characterisation. Given that the comparator used as a digitization device of FE electronics ensures binary readout from strips, the increasing threshold causes the gradual signal disappearance ($1 \rightarrow 0$) for each channel. At each threshold level several charge injections are performed. Therefore, the signal decrement is represented by the efficiency loss, which is defined as a number of triggers with signal divided by total number of triggers.

Signal curve from strips is affected by the noise of electronics that has Gaussian distribution.

![Threshold scan at 3.01 fC](image1.png)

![Threshold scan for bias_400V_10000rg, latency_10](image2.png)

Figure 3.6: Calibration threshold scan with the injected charge equivalent to 3.01 fC (left) and beta source threshold scan (right) having much greater dispersion sigma.

In case of the calibration pulse, which is a delta function, the integral form of resulting curve including noise distribution comes into the shape of error function. The plot of efficiency dependence on the threshold value is known as an S-curve. Fit of the resulting distribution then defines median\(^1\) corresponding to the injected charge in units of ITSDAQ, namely DACs, and dispersion that determines noise of electronics. In case of the beta source test the shape of S-curve comes from the integral form of convolution of Landau distribution (charge deposited by electron) and Gaussian distribution (noise). The median here indicates a charge collected on strips during the passage of electron through the sensor.

\(^{1}\)value with 50% hit rate, called Vt50 in mV or Qt50 in fC
**Strobe Delay**

The basic test that should be done at the beginning of each ITSDAQ run is the Strobe Delay (SD) test. The SD test consists of two scans and sets the delay of an injected calibration pulse with respect to Level 1 Accept (L1A) trigger that issues the pulse [1]. The correct setting ensures synchronisation of the calibration pulse and threshold discriminators to prevent efficiency losses [3.7].

![Figure 3.7: The result of the SD test with the fraction 0.57 is given in nanoseconds.](image)

The fraction of plateau with 100% efficiency, where we take the value of SD, is set to 0.57 in ITSDAQ by default. In case of Prague DAQload SD equals 23 ns. The reason for this setting is the greatest response (gain) and small noise (innse) at room temperature. This peak moves with decreasing temperature to lower values of SD [3.8].

![Figure 3.8: Gain and noise dependence on SD value for different temperatures (red points show usual value during beta tests).](image)

**Trim Range**

The Trim Range or trimming aims at minimizing the channel-by-channel response variations. In twenty threshold scans for different trim DAC settings a charge of 1 fC is injected into channels to find an optimal setting for each channel and to return the same value of median.

Resulting trim files contain a necessary shift of offset, which is defined as a
channel response for zero charge injection, for each untrimmed channel to reach the same response on given threshold (typically 1 - 1.5 fC). The corresponding trim file must be moved from folder with results to folder with configuration files and appropriately renamed. Consequently this trimming is used for each future ITSDAQ run and therefore new Trim Range test needs to be repeated after each change of parameters of chip FE electronics.

**Three Point Gain**

Given no physical meaning of DAC units, a conversion is needed. In general, the conversion to units of injected charge can be dependent on parameters of front-end (FE) electronics, strobe delay, temperature and other circumstances. Any value in DAC units is at first converted to millivolts (mV) using configuration text file ABC130_thrCal.txt that comes from expert simulation of readout ABC130 chip. This conversion will be discussed in Sec. 4.4.

The next step is mV-to-fC conversion that is performed for lower charge values by the Three Point Gain (3PG) test. This test is based on three threshold scans at different injection charges, typically \{0.5, 1.01, 1.51\} fC or \{1.5, 2.01, 2.51\} fC. The response from each channel in form of Vt50 (in mV) is plotted as a function of injected charge and linearly fitted to get a slope of the line (gain) and its constant parameter called offset (pedestal):

\[
V_{t50}[mV] = gain[mV/fC] \times Q_{t50}[fC] + offset[mV]
\]  
(3.1)

Together with average gain and offset value and channel-by-channel analysis also input noise (innse) including rms can be found in resulting text file. The inverted relation (3.1) as well as gain and offset will be later used to obtain correct collected charge in fC.

**Response Curve**

The relation between injected charge and internal units may not be necessarily linear, especially for higher charges. Therefore, an extended test called the Response Curve is available in ITSDAQ, which is based not on three but ten threshold scans going up to 6 fC.

<table>
<thead>
<tr>
<th>Threshold scan</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injected charge [fC]</td>
<td>0.21</td>
<td>0.50</td>
<td>0.81</td>
<td>1.01</td>
<td>1.24</td>
<td>1.51</td>
<td>2.00</td>
<td>3.01</td>
<td>3.99</td>
<td>6.01</td>
</tr>
</tbody>
</table>

Table 3.1: Injected charges of threshold scans during the Response Curve test.

The resulting plot is fitted by a function of 3 parameters \(p_0, p_1, p_2\) again written into text file.

\[
V_{t50}[mV] = \frac{p_0}{1 + \exp \left( \frac{-Q_{t50}[fC]}{p_1} \right)} + p_2
\]  
(3.2)

Given that we are finally interested in inverse relation, we have:

\[
Q_{t50}[fC] = -p_1 \ln \left( \frac{p_0}{V_{t50}[mV] - p_2} - 1 \right)
\]  
(3.3)
Noise Occupancy

The Noise Occupancy scan (NO) measures the noise occupancy of a sensor as a function of discriminator threshold. The noise occupancy is defined as a number of hits for the equivalent threshold of 1 fC. The channel noise occupancy requirement for the ITk strip module is $10^{-3}$ at a threshold with hit efficiency greater than 99% [22]. The channel noise can be also obtained from the linear fit of natural logarithm of noise occupancy dependent on the threshold squared.

3.3.2 Noise

In electronic devices we can not avoid various types of noise affecting signal. Using ITSDAQ software we are able to measure input and output noise, which are not independent. In fact, considering calibration tests described above, the 3PG test or the RC test would be enough for determining both types of noise.

The output noise corresponds to the dispersion factor $\sigma$ of the noise Gaussian distribution that is reflected by sigma measured during threshold scan at a particular injected charge. The input noise (innse in ITSDAQ files) is defined as an injected charge at the input that would simulate the same signal at the output as obtained from the noise. It is generally called the Equivalent Noise Charge (ENC), expressed in electrons ($1 \text{ fC} = 6241 \text{ e}^-$) and equal to
\[ ENC [fC] = \frac{\sigma [mV]}{\text{gain [mV/fC]}} \]  

(3.4)

The average ENC of the Prague DAQload with miniature sensor bonded on the ABC130 single chip is approximately 550 \( e^- \) (Fig. 3.11).

The ABC130 characterisation needs to be done to determine chip electronics influence on the input signal. However, the signal itself induced by beta electrons passing randomly through the sensor should be triggered to achieve exact readout timing. The block diagram of external trigger setup is shown in Fig. 3.12 and explained in the following subsections.

3.4 External Trigger Setup

The ABC130 characterisation needs to be done to determine chip electronics influence on the input signal. However, the signal itself induced by beta electrons passing randomly through the sensor should be triggered to achieve exact readout timing. The block diagram of external trigger setup is shown in Fig. 3.12 and explained in the following subsections.

3.4.1 Beta Source

The irradiation of sensor is performed by strontium isotope \(^{90}Sr\) whose activity according to the reference date should reach 50 kBq and its decay chain can be
found in Tab. 3.2.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$T_{1/2}$ [y]</th>
<th>E [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{90}$Sr</td>
<td>28.79</td>
<td>0.546</td>
</tr>
<tr>
<td>$^{90}$Y</td>
<td>0.0073</td>
<td>2.28</td>
</tr>
<tr>
<td>$^{90}$Zr</td>
<td>stable</td>
<td>stable</td>
</tr>
</tbody>
</table>

Table 3.2: Beta decay chain of strontium source [9].

Beta electrons are collimated by the polymethylmethacrylate collimator with cylindrical hole in the middle (height 9 mm, diameter 5 mm). Its distance from the sensor is adjustable thanks to a screw mounted on a supporting structure. Beta electron passes through the sensor, interacts with silicon and leaves binary signal retained in L0 pipeline with respect to the preset threshold.

Given the spectrum of beta decay takes a specific shape calculated in the Fermi theory as follows [2]:

$$
\frac{d\omega}{dT_e} = C \left( T_e + m_e c^2 \right) \left( T_{max} - T_e \right)^2 \sqrt{T_e^2 + 2T_e m_e c^2}
$$

(3.5)

the electron energy varies and therefore we need more statistics to reduce statistical error of median. In Eq. 3.5 $C$ represents the normalisation constant, $T$ kinetic energy of beta electron, $m_e$ its mass and additionally a coulombic correction factor $F(Z, T)$ called the Fermi function can be added. It is equivalent for non-relativistic betas (e.g. also $^{90}$Sr and $^{90}$Y) to [7]

$$
F(Z, T) = \frac{2\pi \alpha Z}{\beta \left( 1 - e^{-\frac{2\pi \alpha Z}{\beta}} \right)}
$$

(3.6)

where $Z$ is an atomic number of decaying element, $\alpha$ fine-structure constant and $\beta$ the relative electron velocity.

3.4.2 Scintillator

Electrons generated during beta decay pass through the sensor to be detected in scintillator. Scintillation crystal is wrapped by a black kapton tape and connected to the photomultiplier tube. The HAMAMATSU photosensor module H5783, whose outline can be found in Fig. 3.13, is used for this measurement.

![Figure 3.13: Outline of the photosensor](image)

The tube has 4 electric cables and coaxial single cable at the output:
- Power - to power the scintillator (15 V)
- Reference - to return reference voltage from the scintillator (1.2 V)
- Control - to control overall functionality (0.9 V)
- Ground - to be grounded
- Coaxial - to supply an analogue signal from the scintillator

For the purpose of uniform control of all voltages with just one voltage source one can use the voltage divider with 15 V at the input.

3.4.3 Signal Modification

Negative analog pulse supplied from the scintillator must undergo modification to meet the requirements of the Atlys board. Therefore, the Nuclear Instrumentation Module (NIM) crate constitutes an integral part of the setup and allows power supply and connection of modules adapted for this use. The analog signal is supplied to the Constant Fraction Discriminator (CFD) module with Mean Timer (MT) circuit that modifies signal to the digital pulse according to an internal threshold.

![Scintillator_threshold_scan](image1.png) ![Median_vs_scint_thr_bias400V_distance23mm](image2.png)

Figure 3.14: Trigger frequency at zero distance from beta source (left) and independence of the Qt50 on the scintillator threshold (right).

This threshold is mechanically adjustable as well as width of the resulting negative digital signal. On this occasion the scintillator threshold scan was performed to calibrate its default setting with acceptable trigger frequency and without negative effect on hit efficiency or Qt50 value (Fig. 3.14). The scintillator threshold was finally set to 200 mV with the frequency of external trigger $3 \times 10^{-1}$ at the distance of approximately 3 cm.

Given that the Atlys board operates with positive pulses, one extra NIM module should be used in the setup. The Level Adapter single-width module provides two sections, each with 8 input channels, that convert NIM logic levels to the TTL signal as well as in the opposite way. In this context it is able to switch the signal polarity and produce the positive digital TTL signal that finally serves as an external trigger for readout system. All signal modifications are projected on an oscilloscope and shown in Fig. 3.15.
3.5 Prague Laboratories

All tests were carried out on the premises of Charles University in Prague at the Institute of Particle and Nuclear Physics (IPNP). The initial preparation of the beta source test setup (Fig. 3.16) including basic characterisation processes and also beta source tests of the DAQload took place in Clean Room 1 (CR1) to replace laser test setup. The clean room is continuously monitored to maintain a constant temperature and humidity. The supporting structure, including beta source and scintillator placed opposite to each other, was built in a black box to prevent increase of noise and the miniature sensor of the DAQload was positioned about 1 cm over the scintillator. Thanks to a hole in the aluminium pad of the test frame just below the sensor electrons are able to reach the scintillator. After three months of testing at room temperature the experimental setup was moved to Electronic Room (ER) shown in Fig. 3.17 where beta source tests at lower temperatures were performed.

During measurements the institutional computers ipnp03, ipnp28 and ipnp14 with operating system Windows 10 were used.

3.5.1 Additional Equipment

To complete the beta source test setup several details should be supplemented such as power supplies or cold tests equipment:

- High voltage - to deplete sensor bulk, Keithley 2401 as voltage source and detector leakage current meter (5 - 15 nA at 400 V)
- Low voltage - to power up readout chips, Aim-TTi CPX400SP voltage supplies set to 1.55 V/0.26 A and 4.50 V/0.24 A
- Scintillator power supply - to power up photomultiplier by 15 V
• Chiller - to maintain module temperature at the specific value, Julabo CF31 Cryo-Compact Circulator with working temperature range between -30°C and 200°C

• Freezer - to prevent air heat exchange between cooled setup and surroundings

Figure 3.16: Beta source test setup in the black box situated in CR1.

Figure 3.17: Laboratory in ER at IPNP.

Figure 3.18: Strontium beta source. Figure 3.19: Voltage divider and scintillator power supply.
4. Source Tests and Analysis

Testing of the ATLAS ITk Strip module prototypes is performed for detectors before and after irradiation. At the IPNP in Prague all laser or beta source tests are concentrated on the non-irradiated modules. The most critical parameters that should be studied are the collected charge (Qt50), the hit efficiency, the gain and the ENC.

Beta source tests execution itself and subsequent analysis of results requires several steps that have to be done in advance. For this purpose a set of C macros was prepared:

- **ExternalTrigger_BetaSource_ATLYS_daqload.cpp** - main macro for configuration and execution beta source test
- **Beta_vt50.cpp** - analysis for S-curve reconstruction and collected charge value extraction
- **Beta_ClusterAnalysis.cpp** - S-curve reconstruction and cluster analysis

For more details about content of macros see attachments. As an output of the beta source test macro one gets number of text files with event list for each chip and channel corresponding to the number of preset threshold values. This event list contains binary information about possible hit created by threshold discriminators of channels. Given only one ABC130 chip was bonded on the miniature sensor, all following analysis considerations concentrate on this chip.

4.1 Threshold Scan Analysis

S-curve in the context of source tests is a product of threshold scan and expresses dependence of hit efficiency on the threshold value. Two fit options to obtain the collected charge value corresponding to the median are used in the analysis.

4.1.1 Skewed Complementary Error Function Fit

To ensure fully automatic run of the analysis more complicated function is used for S-curve fitting. It is called skewed complementary error function and it can fit the data very precisely. The function has the following form:

\[ f(x) = \epsilon_{max} Erfc \left[ x \left( 1 + 0.6 \frac{e^{-\xi x} - e^{\xi x}}{e^{-\xi x} + e^{\xi x}} \right) \right] \]  \hspace{1cm} (4.1)

It contains four free parameters - mean, sigma, skew factor \( \xi \) and \( \epsilon_{max} \) (half of S-curve maximum). In case of obvious fitting problems, e.g. long straight plateau or sharp edge, \( \epsilon_{max} \) could be fixed for better result or there is a possibility to move to linear fit.

\(^1\)event corresponds to the external trigger
4.1.2 Linear Fit

The linear fit of S-curve is a very good approximation in this case. Given greater errors arising from the other factors appears, linear fit is accurate enough. The fitting method is as follows:

- do threshold scan, plot the S-curve,
- choose fitting interval to obtain plateau using constant function fit,
- fit the S-curve within 0.8 and 0.2 fraction of the obtained plateau height by linear function,
- take the height of the S-curve at its half and using previous linear fit get the value of \( V_{t50} \).

Although this method is simple and accurate, it is not straightforward to get plateau fitting interval automatically because of noise at low thresholds or variable plateau width for different FE parameters setting. Therefore it has to be done manually during each beta source test analysis, which favors skewed complementary error function fit. As it is pictured in Fig. 4.1 differences between both fit options are in order of hundredths of fC, which corresponds to the measurement error of 0.08 fC discussed in Sec. 4.5.

![Figure 4.1: Skewed Erfc fit (left) and linear fit (right).](image)

4.1.3 Cluster Size

The important part of the analysis is so called cluster analysis. The term cluster represents a set of neighboring strips with positive binary signal. The number of strips in this set is then cluster size.

In an effort to reduce noise at low thresholds and to be sure that just the passage of electron is evaluated, specific rules are chosen in the analysis:

- max. 1 cluster per event,
- cluster size smaller than 6.

In Fig. 4.2 the example of cluster analysis for measurement with 1000 events and bias voltage 350 V is shown.
4.2 Sensor Specification

During Prague DAQload source tests two HAMAMATSU miniature sensors were studied with the same ASICs due to poor response from several strips of the first one after cold tests. Therefore, the new sensor was rebonded on the second stream (Stream 1 instead of Stream 0) of the old ABC130 chip. Specification of both tested sensors is attached below:

- ATLAS12A - MINI - VPX12318-W621, EC small pitch C-P17
- ATLAS12A - MINI - VPX12518-W695, EC small pitch C-P17

Sensor series and type is represented by ATLAS12A - MINI label, VPX12318-W621 corresponds to the lot number and wafer number respectively and P17 indicates the position of the small mini sensor on the wafer. Other important information are shown in Tab. 4.1.

<table>
<thead>
<tr>
<th>Substrate type</th>
<th>FZ1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate orientation</td>
<td>&lt;100&gt;</td>
</tr>
<tr>
<td>Substrate resistivity [kOhm*cm]</td>
<td>3 - 8</td>
</tr>
<tr>
<td>Thickness [µm]</td>
<td>325</td>
</tr>
<tr>
<td>Average pitch [µm]</td>
<td>64.3</td>
</tr>
<tr>
<td>Depletion voltage [V]</td>
<td>320 - 380</td>
</tr>
<tr>
<td>Active area [cm²]</td>
<td>0.69</td>
</tr>
<tr>
<td>Strip length [cm]</td>
<td>0.806</td>
</tr>
<tr>
<td>Leakage current [nA/cm²]</td>
<td>4.8</td>
</tr>
<tr>
<td>$C_{int}$ [pF/cm]</td>
<td>0.79</td>
</tr>
<tr>
<td>$R_{bias}$ [MOhm]</td>
<td>1.5</td>
</tr>
<tr>
<td>$R_{int}$ [GOhm]</td>
<td>20 - 80</td>
</tr>
<tr>
<td>Coupling capacitance [pF/cm]</td>
<td>24</td>
</tr>
</tbody>
</table>

Table 4.1: Specification valid for both mini sensors tested at IPNP.
4.3 Beta Source Test Results

In contrast with laser tests and test beams beta source tests do not provide information about the exact position of passing particle. The reason is low energy of beta electrons, which is not sufficient to leave signal in both the detector and the auxiliary telescope unlike test beam measurements. The beta source position was adjustable in z-direction (height above the sensor) and fixed in other directions except angular scans which required source rotation.

Each beta source scan should be preset in the main macro by start and stop threshold ranges, step size and number of external triggers. From the very first tests it was shown that 100 triggers scan with 2 DACs step is enough for determining of the S-curve parameters, but for comparison also more precise measurements were carried out.

To control response from individual strips or possible incorrect readout at the particular threshold (Fig. 4.3) one should check hit maps showing number of hits at any threshold for each channel.

![Hit map of a beta source test without noise reduction using cluster cut-off rules. There is a noticeable dead channel and noisy events at specific threshold which demonstrate some readout problem.]

Hit maps are part of the basic set of histograms in a root file created for a specific ITSDAQ scan or they are independently calculated and plotted as a part of the cluster analysis macro (Fig. 4.4).

However, hit map in this context obviously does not correspond to the set of S-curves for each channel such as in case of ITSDAQ preset calibration scans discussed in previous section because it includes just the hit analysis focused on the response of individual channels, not cluster reconstruction that must be done in case of cluster analysis macro.

4.3.1 Calibration Results

Original Sensor

In an effort to ensure correct conversion from internal DACs to fC several calibration tests were performed during first sensor testing in CR1 and also at low
temperatures in ER. Values of conversion parameters arising from RC or 3PG fit are shown in Tab. 4.2 and relate to at that time default FE parameters setting and appropriate DACs-to-mV conversion file. Difficulties with conversion files and FE parameters setting will be discussed in more detail later in Sec. 4.4.

<table>
<thead>
<tr>
<th>Room</th>
<th>p0</th>
<th>p1</th>
<th>p2</th>
<th>offset [mV]</th>
<th>Scan type</th>
<th>IC (300 mV)</th>
<th>SD</th>
<th>SD fraction</th>
<th>SD Run-scan</th>
<th>RC Run-scan</th>
</tr>
</thead>
<tbody>
<tr>
<td>CR1</td>
<td>1254.74</td>
<td>1.52</td>
<td>-592.49</td>
<td>-</td>
<td>RC</td>
<td>3.10</td>
<td>23</td>
<td>0.57</td>
<td>285-2</td>
<td>287-1</td>
</tr>
<tr>
<td>CR1</td>
<td>1256.58</td>
<td>1.53</td>
<td>-593.40</td>
<td>-</td>
<td>RC</td>
<td>3.18</td>
<td>22</td>
<td>0.57</td>
<td>295-2</td>
<td>290-1</td>
</tr>
<tr>
<td>CR1</td>
<td>1259.91</td>
<td>1.54</td>
<td>-595.78</td>
<td>-</td>
<td>RC</td>
<td>3.19</td>
<td>23</td>
<td>0.57</td>
<td>391-3</td>
<td>393-3</td>
</tr>
<tr>
<td>ER</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>RC</td>
<td>3.87</td>
<td>13</td>
<td>824-3</td>
<td>821-3</td>
</tr>
<tr>
<td>ER</td>
<td>1217.67</td>
<td>4.01</td>
<td>417.91</td>
<td>-</td>
<td>RC</td>
<td>3.87</td>
<td>13</td>
<td>0.40</td>
<td>824-2</td>
<td>820-3</td>
</tr>
</tbody>
</table>

Table 4.2: Comparison of calibrations of the first tested sensor with trimmed channels in chronological order.

Hypothetical value of injected charge equivalent to response of 300 mV serves to compare individual calibration scans between themselves. As apparent from the table small discrepancy about 0.2 fC appeared between RC and 3PG that was not caused just by the nonlinearity of response curve. It will be explained in Sec. 4.6. For all listed Qt50 values in this thesis the correct calibration was used.

Two different SD fraction measurements confirm decrease of gain, which corresponds to the rate of response, from 82 mV/fC to 72 mV/fC as pictured in Fig. 3.8. Therefore, the last two calibrations were not used for the analysis and the initial value of SD fraction equivalent to 0.57 was maintained. In addition, appearance of dead channels required correction in terms of manual exclusion of bad strips from the analysis and subsequent exchange of sensor.

New Rebonded Sensor

The presumption was that the same type of new mini sensor should have the same properties during calibration as the old one. Tab. 4.3 compares calibration scans before and after trimming. The gain and offset values in case of trimmed channels fit very precisely with the old sensor response. Scans with untrimmed channels were not shifted in the offset value as described in Sec. 3.3.1 and therefore the offset value differs.
Table 4.3: List of calibration scans with the new sensor. SD value equals 23 for all at 0.57 fraction.

4.3.2 Source Tests at Room Temperature

During beta source tests at room temperature various dependencies were studied to determine effect on the resulting analysis parameters such as Qt50 or cluster size at 1 fC. Besides mentioned scintillator threshold scan also bias scan, angular scan and FE parameters scans were investigated. Important source test results are summarized in Tab. 4.4 and 4.5.

<table>
<thead>
<tr>
<th>Run</th>
<th>No. of trig.</th>
<th>Step [DACs]</th>
<th>Bias [V]</th>
<th>xAngle [°]</th>
<th>yAngle [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>735</td>
<td>1000</td>
<td>3</td>
<td>450</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>412</td>
<td>1000</td>
<td>1</td>
<td>400</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>416</td>
<td>1500</td>
<td>1</td>
<td>400</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>672</td>
<td>1500</td>
<td>2</td>
<td>400</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>734</td>
<td>1000</td>
<td>1</td>
<td>350</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>686</td>
<td>500</td>
<td>5</td>
<td>250</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>687</td>
<td>500</td>
<td>5</td>
<td>150</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>688</td>
<td>500</td>
<td>5</td>
<td>50</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>730</td>
<td>1000</td>
<td>1</td>
<td>400</td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>731</td>
<td>1000</td>
<td>1</td>
<td>400</td>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td>733</td>
<td>1000</td>
<td>1</td>
<td>400</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>732</td>
<td>500</td>
<td>1</td>
<td>400</td>
<td>0</td>
<td>40</td>
</tr>
</tbody>
</table>

Table 4.4: List of performed runs. The quantity xAngle expresses rotation around axis perpendicular to the strips in the sensor plane and yAngle rotation around axis parallel to the strips.

All these runs were measured at the distance around 2.3 cm except runs 412 and 416 where the source distance from the sensor moved around 0.5 cm, i.e. increase of average cluster size due to wider angular spectrum of incoming electrons.

Angular scan required a shift of the source and the scintillator to ensure that the linear track of electrons from the rotated source passed through the sensor right into the sensitive scintillator crystal (Fig. 4.5). Two interesting options of the setup alignment came into consideration in case of angular scans. By rotation of the beta source around the axis perpendicular to the strips in the sensor plane one can expect increase of the collected charge as well as moderate growth of the cluster size due to longer travelled distance during electron passage along strips.

The simple geometric behaviour of the collected charge expected from the
Table 4.5: Overview of the beta source test results from CR1. Error of measured median considering number of triggers and calibration is analyzed in Sec. 4.5.

Table 4.6: Hypothetical geometric comparison of relative charge collected on the edges and in the middle of sensor.

<table>
<thead>
<tr>
<th>Run</th>
<th>Bias [V]</th>
<th>Avrg CS (1 fC)</th>
<th>Median (Vt50)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Linear Fit</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>DACs mV fC</td>
</tr>
<tr>
<td>735</td>
<td>450</td>
<td>1.36</td>
<td>100.4 291.3 3.05</td>
</tr>
<tr>
<td>412</td>
<td>400</td>
<td>1.42</td>
<td>99.6 288.9 3.02</td>
</tr>
<tr>
<td>416</td>
<td>400</td>
<td>1.42</td>
<td>100.0 290.0 3.03</td>
</tr>
<tr>
<td>672</td>
<td>400</td>
<td>1.29</td>
<td>100.9 292.6 3.07</td>
</tr>
<tr>
<td>734</td>
<td>350</td>
<td>1.33</td>
<td>100.4 291.2 3.05</td>
</tr>
<tr>
<td>686</td>
<td>250</td>
<td>1.21</td>
<td>85.5 249.9 2.51</td>
</tr>
<tr>
<td>687</td>
<td>150</td>
<td>1.12</td>
<td>72.9 215.0 2.07</td>
</tr>
<tr>
<td>688</td>
<td>50</td>
<td>1.01</td>
<td>45.3 138.3 1.17</td>
</tr>
<tr>
<td>730</td>
<td>400</td>
<td>1.36</td>
<td>104.5 302.4 3.20</td>
</tr>
<tr>
<td>731</td>
<td>400</td>
<td>1.53</td>
<td>116.0 333.8 3.64</td>
</tr>
<tr>
<td>733</td>
<td>400</td>
<td>1.82</td>
<td>78.6 230.9 2.27</td>
</tr>
<tr>
<td>732</td>
<td>400</td>
<td>2.21</td>
<td>65.3 194.0 1.82</td>
</tr>
</tbody>
</table>

Figure 4.5: Geometric schema of angular beta source tests.

increased length of path is $1/\cos(\alpha)$, but in reality the relative charge increase is slower (left in Fig. 4.6 and 4.7). This fact could be explained inter alia also by the higher differences in length of path for electrons passing through the sensor in the middle or on the edges. It could play the role especially for larger angles as shown in Tab. 4.6.

Table 4.6: Hypothetical geometric comparison of relative charge collected on the edges and in the middle of sensor.

<table>
<thead>
<tr>
<th>$\alpha$ [°]</th>
<th>$\varphi$ [°]</th>
<th>$\varphi$ [°]</th>
<th>$1/\cos(\alpha)$</th>
<th>$1/\cos(\alpha + \varphi)$</th>
<th>$1/\cos(\alpha - \varphi)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>8.0</td>
<td>8.0</td>
<td>1.00</td>
<td>1.01</td>
<td>1.01</td>
</tr>
<tr>
<td>20</td>
<td>6.9</td>
<td>7.5</td>
<td>1.06</td>
<td>1.12</td>
<td>1.02</td>
</tr>
<tr>
<td>40</td>
<td>4.7</td>
<td>5.4</td>
<td>1.31</td>
<td>1.41</td>
<td>1.21</td>
</tr>
</tbody>
</table>

By rotation of the beta source around the axis parallel to the strips one can expect rapid increase of average cluster size and collected charge decrease due to perpendicular electron passage across more strips which distributes created e-h pairs between more channels. The distributed charge is not counted at the individual discriminators as a hit at higher thresholds (Fig. 4.6 and 4.7).
As follows from source tests at different depletion voltage (bias) the sensor is becoming fully depleted over 350 V where the bias plot shown in Fig. 4.8 saturates.

To estimate the total error of measured median is a complicated task. It consists of the error from calibration, error from S-curve fit and statistical error. The error of S-curve fit could be estimated from Tab. 4.5 where the comparison of two different fit methods is offered. It moves up to 0.05 fC. The statistical and calibration errors will be discussed later.

### 4.3.3 Source Tests at Low Temperatures

The beta source test setup was moved to the freezer in ER to perform tests at low temperatures down to -20°C. The DAQload was separated by perspex from the rest of freezer and fixed by a screw on the cooling jig with special hole under the sensor. Test results are listed in Tab. 4.7. These results shows independence of Qt50 on temperature in range between 15 and -20°C but they are significantly higher (about 0.2 fC) than measurement at 250 V in CR1 as figured in Fig. 4.9.

It can not be caused by change of calibration parameters between rooms as
Figure 4.8: Collected charge depending on the depletion voltage.

<table>
<thead>
<tr>
<th>Run</th>
<th>Temperature [°C]</th>
<th>Avrg CS (1 fC)</th>
<th>Median (Vt50)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Linear Fit</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>DACs  mV fC</td>
</tr>
<tr>
<td>811</td>
<td>15</td>
<td>1.26</td>
<td>90.0 262.6 2.67</td>
</tr>
<tr>
<td>813</td>
<td>0</td>
<td>1.25</td>
<td>90.6 264.2 2.69</td>
</tr>
<tr>
<td>815</td>
<td>-10</td>
<td>1.25</td>
<td>91.0 265.2 2.70</td>
</tr>
<tr>
<td>817</td>
<td>-20</td>
<td>1.27</td>
<td>91.6 266.9 2.73</td>
</tr>
</tbody>
</table>

Table 4.7: Overview of the cold beta source test results with 1000 triggers, 3 DACs step and bias 250 V.

proved in Tab. 4.2, but in Sec. 4.6.2 timing explanation will be suggested after detailed latency scan.

Figure 4.9: Drop of Qt50 value after setup moving between CR1 and ER at 250 V.

4.4 FE Parameters Setting

FE electronics of the ABC130 chip offers the possibility to control voltages and currents referenced to the internal circuit by the internal 5-bit DAC converters. These converters (or parameters) can be adjusted in the configuration file under the abbreviations
• BVREF - to adjust internal bias for voltages VCS, VCD, VCSP, VBASE and VB
• BIREF - to adjust internal bias for bias current generators
• B8REF - to adjust internal bias for 8-bit threshold and calibration DACs
• COMBIAS - to adjust comparator bias
• BIFEED - to adjust preamplifier feedback transistor bias
• BIPRE - to adjust preamplifier input transistor bias

Nominal values recommended by the specification document of the ABC130 ASIC [17] are as follows:

<table>
<thead>
<tr>
<th>Bias</th>
<th>BVREF</th>
<th>BIREF</th>
<th>B8REF</th>
<th>COMBIAS</th>
<th>BIFEED</th>
<th>BIPRE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>13</td>
<td>13</td>
<td>13</td>
<td>16</td>
<td>9</td>
<td>16</td>
</tr>
</tbody>
</table>

As the group from Rutherford Appleton Laboratory (RAL) first showed the change of these parameters can affect pulse shape and thus the gain, noise and possibly also the total response could differ. So far, such a default setting of FE parameters was used during source tests which was preset also at the CERN test beam in July 2016. But that setting was different from the nominal recommendation:

<table>
<thead>
<tr>
<th>Bias</th>
<th>BVREF</th>
<th>BIREF</th>
<th>B8REF</th>
<th>COMBIAS</th>
<th>BIFEED</th>
<th>BIPRE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>11</td>
<td>10</td>
<td>10</td>
<td>9</td>
<td>8</td>
<td>17</td>
</tr>
</tbody>
</table>

Therefore, after the test beam a new simulation of ABC130 response for setting of first three reference parameters equivalent to (11, 10, 10) was requested, because the previously used DACs-to-mV conversion file had been intended for nominal setting (13, 13, 13). The new conversion file existence was announced in autumn 2016 on the occasion of ATLAS Upgrade Week. As the research including this thesis finally proved, the conversion files do not affect value of collected charge in fC but just the value in mV. The calibration can compensate this difference in mV back to the same value in fC. Comparison of these two conversion files is plotted in Fig. 4.10. These files contain values obtained from simulation in mV corresponding to integer DACs units. Thus, these discrete dependencies were fitted for universal use, which involves possible source of error. Up to 250 DACs the discrete values deviation from the fit curve does not exceed 1 DACs in both cases, which is equivalent to 0.03 fC.

However, possible signal variation at different settings of FE parameters remained the object of interest for further research.

Scientists from RAL studied gain and noise values obtained from calibration scans at different setting of FE parameters. They tested full-sized ITk short strip barrel module looking for the best settings. This tuning was done also in Prague laboratory for the DAQload with miniature sensor. Results of these calibration are shown in Fig. 4.11. Analysis of calibration results showed generally lower noise of Prague measurements thanks to shorter strips of mini sensor. But module
response represented here by gain confirmed results from RAL that the most convenient (high gain value and low noise) combination of FE parameters is $(BVREF, BIREF, B8REF, COMBIAS, BIFEED, BIPRE) = (13, 13, 13, 4, 4, 29)$, but it is not recommended setting because it would significantly change the timing behaviour of the chip. The plot clearly determines the most important parameters causing noticeable change of gain or noise value, i.e. $B8REF$ and $BIFEED$.

Figure 4.11: Parameters tuning from STFC RAL (black points) for full-sized short strip barrel module and results from Prague (colored points) for DAQload.
4.4.1 Source Tests for Different FE Parameters Setting

The individual parameters influence on the collected charge value was finally studied to complete FE parameters analysis. At first, beta source tests of the non-reference parameters were performed. The expectations of results should be clear from the description from experts described as follows. The feedback current (BIFEED parameter) defines the impedance of the feedback and has direct impact on the pulse width and peaking time. Nominally this current should be set to 300 nA. Therefore, in case of decreasing BIFEED value the gain, noise and charge collection is becoming better, but it is compromised with the timing issues. This presumption was confirmed as evident from Fig. 4.12.

![Figure 4.12: Dependence of gain and collected charge Qt50 on the value of BIFEED for (BVREF, BIREF, B8REF, COMBIAS, PRE) = (11, 10, 10, 9, 17).](image1)

The timing of external trigger with respect to the readout command should be controlled by latency scan consisting of beta source scans with different delay. This scan is able to detect the width of plateau with maximal response with respect to

![Figure 4.13: Comparison of latency scans for two different BIFEED values. BIFEED trend could not be obviously explained by horizontal shift of plateau in latency scan. Plateau of higher BIFEED value is below the second one, which corresponds with the previous plots. The dashed line represents default latency value for Prague beta source tests.](image2)
to the latency time. It will be explained in Sec. 4.6. No signal leak appeared due to trigger timing reasons in case of BIFEED parameter as shown for comparison of low and high value in Fig. 4.13.

The same research was carried out also for BIPRE and COMBIAS parameters, but no signal dependence appeared. COMBIAS sets the current in the digital part of the discriminator and it does not influence the pulse shape. BIPRE parameter then sets the current in the input transistor.

All performed FE parameters beta source tests in Prague laboratory are shown in Tab. 4.8.

<table>
<thead>
<tr>
<th>Run number</th>
<th>BVREF</th>
<th>BREF</th>
<th>BSREF</th>
<th>COMBIAS</th>
<th>FEED</th>
<th>V&lt;sub&gt;50&lt;/sub&gt; [DCs]</th>
<th>V&lt;sub&gt;50&lt;/sub&gt; [mV]</th>
<th>Gain [mV/fC]</th>
<th>Offset [mV]</th>
<th>p&lt;sub&gt;1&lt;/sub&gt; parameter</th>
<th>p&lt;sub&gt;1&lt;/sub&gt; parameter</th>
<th>p&lt;sub&gt;2&lt;/sub&gt; parameter</th>
<th>Qt&lt;sub&gt;50&lt;/sub&gt; [fC]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1284</td>
<td>11</td>
<td>10</td>
<td>10</td>
<td>9</td>
<td>8</td>
<td>17</td>
<td>100.4</td>
<td>270.1</td>
<td>76.88</td>
<td>43.63</td>
<td>1341.1</td>
<td>4.14</td>
<td>-640.86</td>
</tr>
<tr>
<td>1289</td>
<td>13</td>
<td>13</td>
<td>13</td>
<td>4</td>
<td>4</td>
<td>29</td>
<td>104.6</td>
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Table 4.8: Beta source tests of FE parameters settings performed in Prague laboratory. Gain and offset were obtained from 3PG calibration but the mV-to-fC conversion is ensured by RC fit parameters. The shaded area indicates 3PG measured with the old incorrect macro described in Sec. 4.6. So the gain should be similar, but the offset is probably wrong.

From the table it is obvious that the nominal recommended setting gives about 0.3 fC lower value of collected charge than the other settings. The two last measurements 1574 and 1578 document independence of Qt<sub>50</sub> on the conversion file choice and especially B8REF influence on the collected charge. The disadvantage of nominal setting in terms of lower obtained Qt<sub>50</sub> is compensated by very high gain, about 13% higher than in other cases, and by low ENC as apparent from Fig. 4.14. The plot uses just BIFEED and B8REF parameters because the others do not change significantly noise value.
4.4.2 Laser Tests for Different FE Parameters Setting

In addition, several laser tests were performed in CR1 to confirm the beta source tests results regarding FE parameters settings. These tests without trimming were done for channel 468 with high voltage on the pulse generator set to 2.27 V. Prague laser test setup and measurements are described in [6]. All results are shown in Tab. 4.9.

<table>
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<th>Run number</th>
<th>BVREF</th>
<th>B1REF</th>
<th>B3REF</th>
<th>COMBIAS</th>
<th>FEED</th>
<th>Vt50 [DACs]</th>
<th>Vt50 [mV]</th>
<th>Gain [mV/fC]</th>
<th>Offset [mV]</th>
<th>p0 parameter</th>
<th>p1 parameter</th>
<th>p2 parameter</th>
<th>Qt50 [fC]</th>
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<td>16</td>
<td>16</td>
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<td>4.36</td>
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</table>

Table 4.9: Laser tests performed in CR1 at laser intensity that does not correspond to the response of beta electrons absolutely, but it shows relative difference between FE parameters settings.

The first and the last run in Tab. 4.9 operates with the same FE parameters setting to confirm the laser stability. Laser test results very precisely correspond to beta source test results.

4.5 Estimation of Collected Charge Error

Data processing includes various types of errors. The decision was to investigate statistical error of measured median by simulations based on real data. The number of triggers, thresholds in mV and corresponding efficiencies from a beta source test serves as an input. Simulation macro EfficiencyError.cpp uses text file with

conversion file for (13, 13, 13)
conversion file for (11, 10, 10)
thresholds and efficiencies extracted from specific beta source test for this purpose. Both files can be added to the complex analysis including analysis macros Beta_vt50.cpp and Beta_ClusterAnalysis.cpp after each beta source test.

Figure 4.15: Residuals for 50 triggers.

Figure 4.16: Residuals for 500 triggers.

Figure 4.17: Residuals for 1500 triggers.

The idea was to find out how can binomial variations of measured efficiencies from a beta source test affect uncertainties of median for different number of triggers. Therefore, thousand repetitions of different variations of the beta source test data were performed, resulting individual S-curves were fitted by skewed complementary error function and residuals of Vt50, mean and sigma parameters were plotted into histograms shown in Fig. 4.15, 4.16 and 4.17.

To calculate total residuals in fC it was necessary to include the error of
calibration parameters gain and offset and compose it with the value in mV from simulations. Resulting histogram for 128 channels and residual dependence is shown in Fig. 4.18 and the total root mean squares (rms) of residuals can be found in Fig. 4.19.

Figure 4.18: Residuals in fC for 128 channels obtained from calibration.

Figure 4.19: Dependence of RMS of residuals on number of entries.

Most of performed tests are able to determine value of Qt50 with an accuracy of 0.1 fC. However, for example error of individual points in 3PG or RC is not counted as well as any inaccuracy in value of an injected calibration charge provided by capacitor in the calibration circuit.

4.6 Measurement Discrepancies

4.6.1 Calibration Discrepancy

All institutional computers in Prague laboratories CR1 and ER have undergone ITSDAQ reinstall to the newer version 4635 compiled in MSVC 2015. But the difference between 3PG and RC at any value in mV converted to fC persisted.
This discrepancy was equivalent to 0.2 fC or about 20 mV and as evident from Fig. 4.20 its character was clearly systematic.

After communication with experts it was found that the transformation

\[
\begin{align*}
\text{charges}[0] &= q\text{Centre} - 0.5; \\
\text{charges}[1] &= q\text{Centre}; \quad // 2.00 \\
\text{charges}[2] &= q\text{Centre} + 0.5; \\
\end{align*}
\]

for(Int_t i = 0; i < 3; i++){
    \text{chargesInDAC}[i] = \text{charges}[i]/0.035;
    \text{int dacCounts} = (\text{int})(\text{chargesInDAC}[i] + 0.5);
    \text{charges}[i] = \text{dacCounts} * 0.035;
}

was used in ITSDAQ internal macro ABC130ThreePointGain.cpp did not exactly match with simulations that correspond rather to the transformation

\[
\begin{align*}
\text{charges}[0] &= q\text{Centre} - 0.5; \\
\text{charges}[1] &= q\text{Centre}; \quad // 2.00 \\
\text{charges}[2] &= q\text{Centre} + 0.5; \\
\end{align*}
\]

for(Int_t i = 0; i < 3; i++){
    \text{chargesInDAC}[i] = (\text{charges}[i] - 0.1695)/0.0347;
    \text{int dacCounts} = (\text{int})(\text{chargesInDAC}[i] + 0.5);
    \text{charges}[i] = \text{dacCounts} * 0.0347 + 0.1695;
}

It was immediately updated in the trunk version of ITSDAQ and the problem was fixed. All results in this thesis are converted into fC by RC parameters if not explicitly defined otherwise. This is also the reason why the offset from CR1 calibrations in Tab. 4.2 and the offset from FE parameters tests in Tab. 4.8 differ.

The 3PG macro was updated between these two sets of calibrations and the offset value decreased from 55 mV to 35 mV.

During studying ITSDAQ internal macros one more insufficiency appeared.
In the resulting RC text file containing information about the gain, offset and noise value for individual channels one can find out that values of gain and offset are always equivalent. This incorrect behaviour stems from ABC130Response-CurvePlot.cpp macro where these variables are filled as follows:

\[
\text{the\_gain} = \text{the\_rc}[1] + ((\text{double})\text{charge[special\_point]}*(\text{double}2.0*(\text{double})\text{the\_rc}[2]));
\]
\[
\text{the\_offset} = \text{the\_rc}[1];
\]

Parameters obtained from RC or 3PG fit are written into array \text{the\_rc} and consequently recalculated to gain and offset. However, offset should correspond to the constant fit coefficient, i.e. \text{the\_rc}[0]. This issue is not considered a problem for experts so it has not been fixed yet, but it can be easily rewritten if needed.

### 4.6.2 Atlys Firmware Discrepancy

During transition from the Atlys firmware version a0bf to the new version a102 decrease of collected charge about 0.5 fC was observed. Therefore, detailed latency scan was performed due to a suspicion of timing issues. Latency represents a delay between an external trigger and readout signal. Given latency is adjustable in ITSDAQ software as an integer variable with 25 ns step, the delay unit was used to ensure finer scan of delay.

![Latency Scan Graph]

Figure 4.21: Latency scan for both firmware versions where zero correspond to latency 9.

Detailed research including beta source tests at different delay revealed a shift of latency between Atlys firmware versions about 12.5 ns. Resulting Fig. [4.21](#)
shows drop of response at default latency 10 due to plateau shift. Therefore, the default latency value was set to 11 and in future in case of firmware change it will be always necessary to repeat latency scan.

Latency scan of the old Atlys firmware version a0bf also offers possible explanation of the collected charge drop between CR1 and ER laboratories during temperature scan. Since the latency value 10 in ER correspond to the edge of plateau, just a little bit shorter cabling in CR1 could cause shorter delay and subsequent charge decrease.
5. Discussion

The beta source test results concerning the DAQload module show several aspects that should be discussed. First of all results from DESY and CERN test beams for non-irradiated DAQload module with applied bias 400 V indicate higher collected charge in the range between 3.8 fC and 4.2 fC depending on tested ABC130 chip. The test beam results proved to be in this range for DAQload, short-strip barrel module and long-strip barrel module as well. The value 3.1 fC of collected charge obtained from Prague tests is much more affected by multiple scattering in silicon bulk than in case of high energy particles during test beams. Moreover, the plastic collimator provides still wide angular spectrum of electron directions unlike more parallel beams. These two reasons lead to an increase of average cluster size that in case of Prague perpendicular scan equals 1.33 at 1 fC. Test beam analysis selects the tracks that intersect detector within 15 µm from the centre of the strip and therefore the cluster size at 1 fC is below 1.1 according to [22]. Higher average cluster size in the context of binary readout causes lower collected charge due to its more frequent distribution between multiple strips and loss of the signal below threshold. In addition, Geant4 simulations of SCT modules performed by Pavel Rezníček in [7] showed similar difference between source test and test beam results. The published source test results from CERN correspond to the test beam results thanks to analogue readout using a so called ALiBaVa system.

The test beams operated with the same FE parameters setting as it was used in CR1 and therefore the ENC values can be compared. The average noise of the Prague mini sensor is equivalent to 550 e− while for the short-strip barrel sensor the noise moves around 650 e− and for the long-strip barrel sensor around 900 e−. Increasing noise is in conformity with increasing length of strips and their coupling capacity. Assuming Prague collected charge value one can get decreasing signal-to-noise ratio with increasing strip noise corresponding to 35 in case of mini sensor and 30 (22) in case of short-strip (long-strip) barrel sensor. Irradiated samples by fluences equivalent to the end-of-life of all modules were measured at 500 V with test beam value of collected charge corresponding to 2.2 - 2.8 fC and signal-to-noise around 22 for barrel sensors. Bias voltage can be temporarily raised up to 700 V to increase signal-to-noise ratio (e.g. 26 for barrel sensors).

Statistical error of collected charge was calculated from different gain values of individual chip channels during calibration scan and from simulations depending on the number of triggers. This error moves from 0.08 fC to 0.11 fC for reasonable trigger numbers (more than 50). Error resulting from DACs-to-mV conversion is negligible and equals about 0.03 fC. However, no other ABC130 readout chip was tested in Prague beta source setup and therefore this error does not include chip-to-chip response fluctuations, which are equivalent in case of test beam to 0.2 fC. The total error of collected charge value resulting from Prague beta source tests may be estimated at 0.25 fC including different ASICs.
Conclusion

Finally, the results of the master thesis will be summarized and the outlook to the future will be outlined.

At first, the world’s largest system of accelerators at CERN was introduced focusing on the LHC and the ATLAS experiment. Subsystems of the ATLAS detector were described in detail as well as the future ATLAS Upgrade project. One of the key upgrade of the ATLAS detector, the inner tracker exchange, together with a new all-silicon ITk layout was mentioned and the basic arrangement, assembly and properties of ITk Strip modules were included.

Further, properties of silicon as a detection material were compared with other semiconductors and the principle of silicon doping, p-n junction creation and free charge carriers collecting was introduced. Additionally, interactions of particles in silicon and impacts of radiation on sensors were explained.

The individual components of the beta source test setup were described including readout electronics, used software and external trigger circuit. Basic characterization tests of the readout chip using ITSDAQ software were introduced and the description of additional equipment of two Prague laboratories, where the tests were carried out, was done.

The beta source tests of R0 strip end-cap prototype called DAQload with mini sensor were gradually performed in two Prague laboratories. Most of the results were measured at room temperature in CR1 and at low temperatures in the freezer in ER. All results of the Qt50 value are consistent with (3.1 ± 0.1) fC for the tested ABC130 chip at depletion voltage of 400 V. By including the ENC of 550 e− the signal-to-noise ratio corresponds to 35. The Qt50 error is also affected by readout from different ABC130 chips, which is equivalent to the additional error of 0.2 fC as shown at test beams. Lower collected charge obtained from Prague beta source tests compared to the test beam value (4 fC) was discussed in Sec. 5 and is caused by the higher average cluster size associated with multiple scattering process and insufficient collimation of beta electrons. Beta source tests from CERN confirm the test beam results using analogue readout from strips in contrast with binary readout in case of Prague tests, which should be used for future ITk operation. Besides temperature scan various other dependencies were studied such as bias, angular, latency or FE parameters scan.

More detailed investigation was performed for the influence of individual FE parameters settings on the collected charge value. Changes of the Qt50 value correlated with changes of the gain for different setting. The most significant change of collected charge value was observed for change of FE parameters B8REF and BIFEED. After these measurements experts admitted that for these parameters the signal pulse shape may be modified and therefore the median value would change. In this context the currently used default setting of parameters BVREF, BIREF and B8REF (13, 13, 13) gives a response of about 0.3 fC lower and the ENC of about 50 e− lower than the previously used setting (11, 10, 10).

The latency scan was able to explain response discrepancy of about 0.2 fC between laboratories by shorter cabling in CR1 because the latency value 10 corresponded to the edge of maximal response plateau in ER. This scan detected also a drop of response for the new version of Atlys firmware. The plateau of
maximal response was shifted by 12.5 ns and therefore the latency value had to be changed to 11 (25 ns shift).

In addition, a complete set of testing and analysis C++ scripts was written to provide basic beta source test or FE parameters scan execution, cluster analysis and S-curve reconstruction.

All the scripts together with the beta source test setup are prepared for the production phase of the ITk Upgrade project.
Bibliography


[17] *ABC130 ASIC Specification v4.5*, [online], available from http://indico.cern.ch/event/249047/material/0/0?contribId=1, [cit. 2017-04-12]


### List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Large Hadron Collider including collision points.</td>
<td>5</td>
</tr>
<tr>
<td>1.2</td>
<td>Layout of the ATLAS detector [21].</td>
<td>6</td>
</tr>
<tr>
<td>1.3</td>
<td>Long-term High Luminosity LHC upgrade plan [12].</td>
<td>7</td>
</tr>
<tr>
<td>1.4</td>
<td>Inclined layout of the new all-silicon tracker [22].</td>
<td>8</td>
</tr>
<tr>
<td>1.5</td>
<td>Staves and petals layout [13].</td>
<td>8</td>
</tr>
<tr>
<td>1.6</td>
<td>Assembly of short-strip barrel module [22].</td>
<td>9</td>
</tr>
<tr>
<td>1.7</td>
<td>Module electronics overview [18].</td>
<td>9</td>
</tr>
<tr>
<td>2.1</td>
<td>Scheme of gaps between valence and conduction band for (a) conductors with partially filled conduction band or with the overlapping bands, (b) semiconductors and (c) insulators [8].</td>
<td>11</td>
</tr>
<tr>
<td>2.2</td>
<td>Comparison of semiconductors properties [15].</td>
<td>11</td>
</tr>
<tr>
<td>2.3</td>
<td>Schematic tetravalent lattice for a) n-type silicon with donor (As) and b) p-type silicon with acceptor (B) [8].</td>
<td>14</td>
</tr>
<tr>
<td>2.4</td>
<td>Donor and acceptor energy levels in a forbidden band of silicon. Energy values above the dashed line are calculated from the upper edge and below the dashed line from the lower edge [8].</td>
<td>14</td>
</tr>
<tr>
<td>2.5</td>
<td>a) Charge carriers concentration in the region of p-n junction and b) the distribution of an electric field with marked built-in potential [8].</td>
<td>16</td>
</tr>
<tr>
<td>2.6</td>
<td>Normalized Landau-Vavilov-Bischel energy loss probability distribution in silicon for 500 MeV pions [10].</td>
<td>18</td>
</tr>
<tr>
<td>2.7</td>
<td>Depletion voltage and concentration of charge carriers for different fluence values of irradiation [11].</td>
<td>19</td>
</tr>
<tr>
<td>3.1</td>
<td>ABC130 Short-Strip Barrel Module (left), Long-Strip Barrel Module (centre) and end-cap DAQload (right) [22].</td>
<td>21</td>
</tr>
<tr>
<td>3.2</td>
<td>Block diagram of the ABC130 chip [22].</td>
<td>22</td>
</tr>
<tr>
<td>3.3</td>
<td>Atlys connection in beta test setup.</td>
<td>22</td>
</tr>
<tr>
<td>3.4</td>
<td>Digilent Adept software and Atlys configuration.</td>
<td>23</td>
</tr>
<tr>
<td>3.5</td>
<td>The Burst Data window of the ITSDAQ software.</td>
<td>24</td>
</tr>
<tr>
<td>3.6</td>
<td>Calibration threshold scan with the injected charge equivalent to 3.01 IC (left) and beta source threshold scan (right) having much greater dispersion sigma.</td>
<td>25</td>
</tr>
<tr>
<td>3.7</td>
<td>The result of the SD test with the fraction 0.57 is given in nanoseconds.</td>
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</tr>
<tr>
<td>3.8</td>
<td>Gain and noise dependence on SD value for different temperatures (red points show usual value during beta tests).</td>
<td>26</td>
</tr>
<tr>
<td>3.9</td>
<td>Three Point Gain (left) and Response Curve (right) for bonded stream 1 and unbonded stream 0.</td>
<td>28</td>
</tr>
<tr>
<td>3.10</td>
<td>Comparison of 3PG and RC calibration scans.</td>
<td>28</td>
</tr>
<tr>
<td>3.11</td>
<td>Channel-by-channel value of input noise at the default setting of PE parameters. Stream of the ABC130 chip consists of 128 channels.</td>
<td>29</td>
</tr>
<tr>
<td>3.12</td>
<td>Block diagram of external trigger circuit.</td>
<td>29</td>
</tr>
<tr>
<td>3.13</td>
<td>Outline of the photosensor [3].</td>
<td>30</td>
</tr>
</tbody>
</table>
3.14 Trigger frequency at zero distance from beta source (left) and independence of the Qt50 on the scintillator threshold (right).

3.15 Analog signal from scintillator (purple), negative digital pulse from CFD module (yellow) and positive digital TTL pulse from Level Adapter (green).

3.16 Beta source test setup in the black box situated in CR1.

3.17 Laboratory in ER at IPNP.

3.18 Strontium beta source.

3.19 Voltage divider and scintillator power supply.

4.1 Skewed Erfc fit (left) and linear fit (right).

4.2 No. of entries vs. threshold vs. cluster size (left) and average cluster size vs. threshold (right).

4.3 Hit map of a beta source test without noise reduction using cluster cut-off rules. There is a noticeable dead channel and noisy events at specific threshold which demonstrate some readout problem.

4.4 Fine scan in CR1 including 1 dead strip (left) and coarse low temperature scan in ER including more dead channels (right).

4.5 Geometric schema of angular beta source tests.

4.6 Relative collected charge dependence on the angle for rotation around axis perpendicular to the strips in the sensor plane (left) and around axis parallel to the strips (right). The red dotted line corresponds to geometric relation.

4.7 Average cluster size (at 1 fC) dependence on the angle for rotation around axis perpendicular to the strips in the sensor plane (left) and around axis parallel to the strips (right). The red line corresponds to the fit with a parabola to guide the eye.

4.8 Collected charge depending on the depletion voltage.

4.9 Drop of Qt50 value after setup moving between CR1 and ER at 250 V.

4.10 Conversion file recommended for the nominal FE setting (13, 13, 13) fitted by polynomial function of degree 4 (blue) and the new conversion file recommended for test beam FE setting (11, 10, 10), used during CR1 measurements and fitted by linear function (black).

4.11 Parameters tuning from STFC RAL (black points) for full-sized short strip barrel module and results from Prague (colored points) for DAQload.

4.12 Dependence of gain and collected charge Qt50 on the value of BI-FEED for (BVREF, BIREF, BSREF, COMBIAS, PRE) = (11, 10, 10, 9, 17).

4.13 Comparison of latency scans for two different BIFEED values. BI-FEED trend could not be obviously explained by horizontal shift of plateau in latency scan. Plateau of higher BIFEED value is below the second one, which corresponds with the previous plots. The dashed line represents default latency value for Prague beta source tests.

4.14 Noise values for different FE parameter settings.

4.15 Residuals for 50 triggers.
List of Tables

3.1 Injected charges of threshold scans during the Response Curve test. 27
3.2 Beta decay chain of strontium source $^{9}$ 30
4.1 Specification valid for both mini sensors tested at IPNP. 36
4.2 Comparison of calibrations of the first tested sensor with trimmed channels in chronological order. 38
4.3 List of calibration scans with the new sensor. SD value equals 23 for all at 0.57 fraction. 39
4.4 List of performed runs. The quantity xAngle expresses rotation around axis perpendicular to the strips in the sensor plane and yAngle rotation around axis parallel to the strips. 39
4.5 Overview of the beta source test results from CR1. Error of measured median considering number of triggers and calibration is analyzed in Sec. 4.5. 40
4.6 Hypothetical geometric comparison of relative charge collected on the edges and in the middle of sensor. 40
4.7 Overview of the cold beta source test results with 1000 triggers, 3 DACs step and bias 250 V. 42
4.8 Beta source tests of FE parameters settings performed in Prague laboratory. Gain and offset were obtained from 3PG calibration but the mV-to-fC conversion is ensured by RC fit parameters. The shaded area indicates 3PG measured with the old incorrect macro described in Sec. 4.6. So the gain should be similar, but the offset is probably wrong. 46
4.9 Laser tests performed in CR1 at laser intensity that does not correspond to the response of beta electrons absolutely, but it shows relative difference between FE parameters settings. 47
# List of Abbreviations

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3PG</td>
<td>Three Point Gain</td>
</tr>
<tr>
<td>ABC</td>
<td>ATLAS Binary Chip</td>
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<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>ALiBaVa</td>
<td>A Liverpool, Barcelona, Valencia (system)</td>
</tr>
<tr>
<td>ALICE</td>
<td>A Large Ion Collider Experiment</td>
</tr>
<tr>
<td>ASIC</td>
<td>Application-Specific Integrated Circuit</td>
</tr>
<tr>
<td>ATLAS</td>
<td>A Toroidal LHC Apparatus</td>
</tr>
<tr>
<td>CERN</td>
<td>Conseil Européen pour la recherche nucléaire (Europeans Organization for Nuclear Research)</td>
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<tr>
<td>CFD</td>
<td>Constant Fraction Discriminator</td>
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<tr>
<td>CMOS</td>
<td>Complimentary Metal Oxide Semiconductor</td>
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<tr>
<td>CMS</td>
<td>Compact Muon Solenoid</td>
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<tr>
<td>CR1</td>
<td>Clear Room 1</td>
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<tr>
<td>CSC</td>
<td>Cathode Strip Chamber</td>
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<tr>
<td>DACs</td>
<td>DAQ Counts</td>
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<tr>
<td>DAQ</td>
<td>Data Acquisition</td>
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<tr>
<td>DC</td>
<td>Direct Current</td>
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<tr>
<td>DESY</td>
<td>Deutsches Elektronen-Synchrotron</td>
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<tr>
<td>ENC</td>
<td>Equivalent Noise Charge</td>
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<tr>
<td>EoS</td>
<td>End of Structure</td>
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<tr>
<td>ER</td>
<td>Electronic Room</td>
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<tr>
<td>FCAL</td>
<td>Forward Calorimeter</td>
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<tr>
<td>FE</td>
<td>Front-end (Front Electronics)</td>
</tr>
<tr>
<td>GBT</td>
<td>GigaBit Transceiver</td>
</tr>
<tr>
<td>HCC</td>
<td>Hybrid Control Chip</td>
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<tr>
<td>HEC</td>
<td>Hadronic End-cap</td>
</tr>
<tr>
<td>HEP</td>
<td>High Energy Physics</td>
</tr>
<tr>
<td>HL-LHC</td>
<td>High Luminosity LHC</td>
</tr>
<tr>
<td>HSIO</td>
<td>High Speed Input Output</td>
</tr>
<tr>
<td>IBL</td>
<td>Insertable B-Layer</td>
</tr>
<tr>
<td>ID</td>
<td>Inner Detector</td>
</tr>
<tr>
<td>IDC</td>
<td>Insulator-displacement Connector</td>
</tr>
<tr>
<td>IPNP</td>
<td>Institute of Particle and Nuclear Physics</td>
</tr>
</tbody>
</table>
ITk    Inner Tracker
ITSDAQ ITk Strips DAQ
LAr    Liquid Argon
LHC    Large Hadron Collider
Linac  Linear accelerator
LS1    Long Shutdown 1
LVDS   Low-voltage Differential Signaling
MDT    Monitored Drift Tubes
MoEDAL Monopole and Exotics Detector at the LHC
MSVC   Microsoft Visual C++
MT     Mean Timer
NIM    Nuclear Instrumentation Module
NO     Noise Occupancy
PCB    Printed Circuit Board
PS     Proton Synchrotron
RAL    Rutherford Appleton Laboratory
RC     Response Curve
RMS    Root Mean Square
ROD    Read-out Driver
RPC    Resistive Plate Chamber
SCT    Semiconductor Tracker
SD     Strobe Delay
SPL    Superconducting Proton Linac
SPS    Super Proton Synchrotron
STFC   Science and Technology Facilities Council
TGC    Thin Gap Chamber
TileCal Tile Calorimeter
TOTEM  Total cross section, Elastic scattering and diffraction dissociation Measurement
TRT    Transition Radiation Tracker
TTC    Trigger, Timing and Control
TTL    Transistor-transistor Logic
USB    Universal Serial Bus
Attachments

Beta Source Test Execution

The main script for beta source test execution called ExternalTrigger_BetaSource-_ATLYS_daqload.cpp is executable from ITSDAQ session and is based on the following commands. After saving the initial state of scan parameters, the setting of specific scan variables is performed:

```c++
  e->SaveState();
  e->StOutScanReset();
  e->ascii_nt=0;
  e->abort=1;
  e->do_cal_loop=0; // cal loop OFF (faster testing)
  e->ConfigureVariable(10, 7); // All lines
  e->LiA_per_loop = 1;
  e->throw_away=0;
  e->do_autostop=1;
  e->ConfigureVariable(1522,0); // set calpol
  e->ConfigureVariable(14,0); // Route Mask OFF
  e->ConfigureVariable(11,0); // any hit mode (for compression mode 01X choose 2 instead of 0)
  e->ConfigureVariable(1004,11); // latency setting
```

Next step is to characterize the output of the scan. It allows a creation of event list for each channel and each chip:

```c++
  e->burst.fill_delta_t = false;
  e->burst.read_tdc_data = false;
  e->burst.save_raw_event_data = false;
  e->burst.save_trigger_data = false;
  e->burst.fill_evtree = false;
  e->burst.fill_tree_counter = false;
  e->burst.send_signals = false;
  e->burst.save_event_hit_data = true; // crucial setting
```

```c++
  e->burst.external_trigger_source = 0;
  e->burst.trtype = 25; // internal trigger type
  e->burst.ntrigs = trigs; // number of triggers (events)
```

Finally, the scan should be configured including threshold ranges and step. At the end of the scan the initial parameters are restored:

```c++
  e->ConfigureScan(1, from, to, step);
  st_scan(21, -1); // run the scan
  e->RestoreState();
```
Additionally, the analysis scripts are immediately called after the end of beta source scan.

**Cluster Analysis**

The cluster analysis script called Beta_ClusterAnalysis.cpp contains reconstruction of clusters from event data files and their subsequent analysis. After initial setting of scan parameters obtained from the beta source test macro and supplemented by chip and stream number one can do a reconstruction of clusters using this sequence:

```c
while (!feof(f)) { // search in the entire event file
    fgets(str, 150, f);
        if (Test_of_noise(str) == 1) { // mentioned cut-off rules
            numoftrig++; // number of true events
            for (int j = 0; j <= strlen(str); j++) {
                if (str[j] == '1') {
                    int clsize = 0;
                    while (str[j] == '1') {
                        clsize++;
                        channelentries[j-6]++;
                        j++;
                    }
                    if (clsize < 6) clustersize[clsize - 1]++; // counting
                }
            }
        }
    }
}
```

The sequence is repeated for each event file corresponding to the different threshold value and resulting histograms, which are plotted at the end, are filled by the reconstructed clusters.

**Reconstruction of S-curve Parameters**

The most important part of the analysis includes determining of the 50% point of a specific S-curve in the script called Beta_ClusterAnalysis.cpp. The S-curve is reconstructed by a similar way as it was done in case of cluster analysis. Additionally, the efficiency value is there introduced as a total sum of clusters divided by the number of true events (0 or 1 cluster by event) at the specific threshold.
In most cases the fit option represented by a skewed complementary error function is chosen. It is defined as follows

double SkewedComplErrorFunction(double *VThr, double *Par) {
    double x = (VThr[0] - Par[0]) / (TMath::Sqrt(2) * Par[1]);
    double value1 = TMath::Exp(-Par[2] * x);
    double value2 = TMath::Exp(Par[2] * x);
    double value = 0.6 * (value1 - value2) / (value1 + value2);
    value = x * (1 + value);
    double y = Par[3] * TMath::Erfc(value);
    return y;
}

and the fitting procedure is ensured by commands

TF1 *func = new TF1("FitSkF", SkewedComplErrorFunction, 21, 200, 4);
h2->Fit("FitSkF", "R+"); // h2 represents S-curve histogram

The fact that the mean parameter of the fit corresponds to the Qt50 value is verified by investigation of the histogram with the very fine step:

double parTemp[4];
func->GetParameters(parTemp); // get fit parameters
double OutVT50 = 0.0;
for (int i = 0; i < 15001; i++) { // iterations
    double VThr;
    double y;
    VThr = 10.0 * i / 300.0;
    y = SkewedComplErrorFunction(&VThr, parTemp);
    if ((OutVT50 == 0) && (y <= parTemp[3])) {
        OutVT50 = VThr;
        printf("-- step %i (%5.3f) Vt50 %4.1f\n", i, y, OutVT50);
        break;
    }
}

The parameter parTemp[3] corresponds to the half of the S-curve maximum. All scripts are available on request if interested.